A COMPARATIVE STUDY OF
TEMPERATURE FLUCTUATIONS IN DIFFERENT
PARTS OF THE HUMAN BODY

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A COMPARATIVE STUDY OF TEMPERATURE FLUCTUATIONS IN DIFFERENT PARTS OF THE HUMAN BODY.

Part I.—Introduction.

The normal body-temperature is a resultant of two factors, thermogenesis, or the development of heat inside the body; and thermolysis, the loss of heat from the body. Usually these two factors are so delicately adjusted as to be nearly equal in value and hence the resulting temperature of the body does not alter materially. When there are marked disturbances in either factor, we have changes in body-temperature. Innumerable experiments[1] have been made to investigate the factors influencing both thermogenesis and thermolysis, and it has been proved that the most important factor affecting thermogenesis is muscular work, either voluntary or involuntary, while the most important factor affecting thermolysis is the temperature environment; this latter is particularly true of small animals.

A knowledge of the fluctuations in body-temperature is of inestimable value to the physician as an index of the body condition; in health the normal limits are rarely exceeded, and consequently increased temperature indicates that radical measures must be taken. To the physiologist, also, a knowledge of the course of the normal body-temperature is important, and when experiments on calorimetry are attempted this factor has especial significance.

HEAT PRODUCTION.

By means of modern apparatus, an accurate measurement may now be made of the total heat given off from the body of a man during an experimental period by the three paths of conduction, radiation, and the latent heat of water vaporized. This of itself is an important contribution to physiology, but of still greater importance is the measurement of the total heat production. The heat production may or may not be the same as the heat elimination, since any discrepancy between thermogenesis and thermolysis causes a change in body-temperature resulting in the loss of a certain amount of heat previously stored, or the storage of heat to be subsequently eliminated. This may be shown by a simple calculation:

From the results of a large number of experiments, a standard value for heat production has been computed for a man weighing 66.6 kilograms, while at rest and asleep.[2] Owing to its large content of water, the body has the

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[1] A historical development of the study of body-temperature, including methods, is given in the excellent article by Pembrey in Schaefer's Textbook of Physiology, vol. 1, 1898, p. 785. This article also includes an extensive statement of literature up to the date of publication.

[2] Benedict and Carpenter, Pub. No. 126, Carnegie Institution of Washington, 1910, p. 253.

somewhat high specific heat of approximately 0.83;[1] the body of a man weighing 66.6 kilograms would consequently have a hydrothermal equivalent of about 55 kilograms of water, so that a change in its temperature of 0.1° C. would produce either a storage or a loss of 5.5 calories of heat. According to the standard value which has been computed, the heat production of a man of this weight and under these conditions would be 71 calories; consequently the amount of heat absorbed or given up by the body as a result of the change in temperature of 0.1° C., i. e., 5.5 calories per hour, would be approximately 7.7 per cent of the total. This discrepancy is too great to permit the measurement of the heat elimination to be taken as an index of the heat production.

Practical experience has shown that a change in temperature amounting to 0.1° C. is very likely to occur, even with enforced body quiet and rest; as a matter of fact, a normal variation in temperature amounting to 1.5° C. is easily possible in a period of 24 hours. If, as is wholly unlikely, such a large variation as 1.5° C. should take place in a shorter experimental period as, for instance, 1 hour, there would be, under the conditions previously cited, a liberation or storage of heat of 82.5 calories. If this heat were stored instead of being eliminated, it is quite conceivable that during the 1-hour period the body would produce heat at such a rate as to raise its temperature 1.5° C., with the elimination of absolutely no heat. While such conditions are physiologically impossible in so short a period, yet when physiologists are attempting to measure the heat production for periods of 1 hour or less a knowledge of even slight variations in body-temperature is of great importance.

The determination of the fluctuations in body-temperature in 24-hour respiration calorimeter experiments is not of particular importance, since one would expect to find approximately the same body-temperature at approximately the same hour of the day; thus, all of the earlier experiments published by Atwater and Benedict[2] were planned on the assumption that at 7 o'clock in the morning (the end of the 24-hour period) the body composition of a subject existing on a uniform diet was constant from day to day, and the body-temperature returned to essentially the same level at this time. When the attempt is made, however, to shorten the experimental periods to 8 hours, 6 hours, 2 hours, or even less, an exact knowledge of the body-temperature at the beginning and end of each period becomes of more and more importance. By means of respiration calorimeters,[3] it is now perfectly feasible to measure the chemical factors of metabolism, namely, the carbon dioxide excretion, oxygen consumption, and water vaporization, in periods of 1 hour; indeed, in the past few months, experimental periods of three-quarters of an hour have been successfully carried out and made a part of the regular routine of this laboratory. The heat eliminated can be likewise measured, and it remains only to make an accurate measurement of the body-temperature to secure the data for computing with considerable exactness the heat production during these periods.

[1]Pembrey, loc. cit., p. 839.
[2]Atwater and Benedict, U. S. Dept. Agri., Office Exper. Sta., Bull. 136, 1903.
[3]Benedict, Riche and Emmes, Am. Journ. Physiol., 1910, 26, p. 1.

DIRECT AND INDIRECT CALORIMETRY.

The data regarding the heat production in short periods are especially valuable in demonstrating the accuracy of so-called indirect calorimetry as compared with direct calorimetry—a demonstration which is of great theoretical as well as practical importance. Such a comparison has been repeatedly made for periods of 24 hours[1] by Atwater and associates, and while the methods of these investigators differ somewhat from those used by Zuntz, it has been shown conclusively that indirect calorimetry for periods of this length is extremely accurate. This demonstration, however, is of little practical value. In the first place, in relatively few instances is the total carbon dioxide excretion for 24 hours determined from which the heat production can be calculated. Secondly, it is extremely rare that the total oxygen consumption for this period is determined. Practically all of the computations made by the Zuntz school have been based upon experiments of 15 to 40 minutes' duration. It becomes, therefore, of fundamental importance to demonstrate the relationship between the gaseous exchange and the heat production not only in periods of 24 hours but in short periods, also.

The calculation of the total metabolism from the data regarding the nitrogen excretion, the carbon-dioxide excretion, and the oxygen consumption assumes that the nitrogen and the carbon dioxide excreted and the oxygen consumed during a given period represent direct molecular transformations which resulted in an energy transformation during that period; that is, that there was no material delay in the oxidative processes; that there was no accumulation of either oxygen or carbon dioxide in the system; and that the nitrogen corresponded to the protein broken down during the period under investigation. Considerable criticism has been made of this method of calculation, but in all probability, if proper precautions are taken to secure constant conditions of diet for a sufficiently long period beforehand, there will be a general uniformity in metabolism; and while the metabolism actually measured in any hour period, as for instance, between 8 and 9 a. m., may not represent the exact transformation during the period, nevertheless it does represent a certain definite average transformation which is approximately accurate. Until, however, it has been clearly demonstrated that indirect and direct calorimetry agree even for short periods, we can place no absolute dependence upon observations and calculations based upon indirect calorimetry.

PURPOSE OF THE RESEARCH.

To sum up, then, it is possible for us to measure with great accuracy the carbon-dioxide excretion, oxygen consumption, water vaporization, and nitrogen excretion during any given experimental period. We can likewise measure with considerable accuracy the heat eliminated by radiation, by conduction, and in the latent heat of water vaporized. On the other hand, we find great

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[1]Atwater and Benedict, loc. cit.; also Benedict and Milner, U. S. Dept. Agri., Office of Exper. Sta., Bull. 175, 1907.

difficulty in computing exactly the heat production, since this is dependent upon an accurate measure of the body-temperature. In any method of measurement thus far devised, the important assumption must be made that the human body as a whole undergoes an average change in temperature corresponding to the fluctuations found by measuring the temperature of any one portion of the body. This last assumption has been based on such uncertain evidence up to the present, that it has seemed desirable to investigate more carefully the fluctuations in temperature of the different parts of the body.

In taking up this problem, we were at once confronted with two rather important questions: First, where is the best place to take the temperature of the body; and second, are the fluctuations in temperature uniform throughout the body? Certain reasoning might here be brought forward to prove that the blood, being a great distributor of heat, equalizes the temperature throughout the whole body, so that we should expect the temperature changes in the different parts to follow a parallel course. If all parts of the body were of essentially the same temperature, this might be easily assumed without question; as a matter of fact, the temperature is not uniform, there being, as one would naturally expect, a sharp thermal gradient. The accurate measurement of the surface temperature presents many difficulties, but as a result of numerous observations made by different methods, 32° C. has been commonly accepted as a standard, and is probably not far from the true value. The temperature inside the body, on the other hand, is known to be not far from 37° C.; we have here, therefore, a gradient of 5° C. This gradient should be very carefully studied before assuming that the temperature in different parts of the body remains constant throughout the whole series of experiments. If the source of heat is constant, as evidenced by the interior temperature of the body, and the temperature of the environment does not change, there is every reason for believing it probable that the gradient will be constant.

Accordingly, in this particular research we have made a simultaneous study of body-temperature, with reference to determining: (1) the best place for an accurate and constant measurement of body-temperature; (2) the temperature gradient of the body; and especially (3) whether or not the temperature fluctuations occurring in the different parts of the body are uniform.

LOCALITIES FOR TEMPERATURE MEASUREMENT.

NATURAL CAVITIES.

A physical examination of the body shows that there are a number of natural cavities which provide favorable opportunity for measuring the body-temperature, since they are surrounded by living tissue and not subjected to the immediate effects of the external environmental temperatures. Of these cavities, by common consent of practically all physiologists, the rectum is considered to be the most favorable and to indicate the truest temperature of the interior of the body. Its use, however, is practicable only in experiments with patients who are bed-ridden and in physiological tests. With female

subjects under similar conditions, the vagina is also an admirable place for making temperature observations.

Rectum.—In taking the temperature in the rectum, it is of prime importance first to note that the thermometer should not be imbedded in fecal matter, as otherwise there may be a sluggishness in the records. This is particularly necessary with glass clinical thermometers, which are sufficiently rigid to become easily imbedded in a mass of fecal matter. Again, the thermometer must be inserted deep enough in the rectum to make sure that the record is not affected by the temperature of the outside air. This latter point will receive special consideration later.

Mouth.—In the private practice of a physician, the rectum and the vagina are practically precluded in the majority of instances and recourse is had to taking the temperature in the mouth. While it is true that the cavity in the mouth underneath the tongue is surrounded by living tissue and protected, at least in part, from the external environmental temperature, nevertheless the cold air from the nasal passages, the frequent breathing through the mouth, and the rapid vaporization of water by the relatively dry air entering the mouth usually produce a supercooling of this cavity. This supercooling may be very noticeable, particularly after severe exercise.[1]

Stomach.—The stomach has been rarely used in measuring body-temperature, since it is somewhat difficult for subjects to swallow a stomach tube with any degree of comfort. While there are relatively few instances in which a fistula has been employed for such measurements, a most interesting series of observations has been made on the temperature in the stomach during digestion, beginning with the early experiments of William Beaumont[2] on Alexis St. Martin, and continuing with the more recent experiments of Rancken and Tigerstedt.[3] Under ordinary conditions, however, it is practically impossible to measure the temperature in this way.

Bladder.—So far as we know, no records of the body-temperature have been taken in the bladder by means of a thermometer inserted through a catheter; nevertheless, mention should be made of the extremely ingenious method first suggested by Stephen Hales[4] of measuring the temperature of freshly voided urine which represents very nearly the temperature of the interior of the body. In such observations it is evident that the time during which the temperature can be taken is relatively short, depending upon the volume of urine passed. Furthermore, the thermometers used should be very sensitive and should first be warmed by the hand or in the mouth to nearly the temperature of the body before placing the bulb in the stream of urine.

[1] Williams and Arnold: Phila. Med. Journ., **3**, p. 1233.
[2] Beaumont, Experiments and observations on the gastric juice and the physiology of digestion, Plattsburgh, 1833.
[3] Rancken and Tigerstedt, Biochem. Zeitsch., 1908, **11**, p. 36.
[4] Hales, Statical Essays, London, 1731, 2d ed., **1**, p. 59.

ARTIFICIAL CAVITIES.

Axilla.—In addition to the natural cavities of the body, there are certain artificial cavities which can be formed by a movement of the limbs, or the folds of the skin, the most important being the axilla. In the normal position of the arm, the axilla provides a natural cavity which needs only to be carefully closed in order to approximate an interior cavity of the body. The axilla is, however, for a good part of the time exposed to a temperature environment not far from 32° C., *i. e.*, the surface temperature of the body, instead of 37° C., that of the interior of the body. The presence of moisture, sweat glands, and hair all combine to make this cavity somewhat difficult to use.

Groin.—Another locality which has been found of great value is the groin. Particularly is this useful in taking the temperature of small infants when clinical thermometers can not be used in either the mouth or the rectum for fear of breakage. Unless subjects are emaciated, it may also be used very satisfactorily with adults after the cavity has become warmed to the temperature of the body.

Other cavities.—Other artificially prepared cavities may be secured by crossing the legs, the temperature being taken inside of the thighs; and by holding the thermometer between the two hands, and obtaining the temperature of the palms. These cavities, however, are not generally used for measuring the body-temperature in either medical practice or physiological experimenting.

SURFACE TEMPERATURE.

The temperature of the exposed surface of the body can be taken at any point, but, as has already been stated, such observations present many difficulties. Any form of thermometer that may be used is not only subject to the temperature of the body, but also to that of the cooler outside environment; and while this discrepancy may be somewhat lessened by artificial warming, such measures are at best unsatisfactory and inaccurate. Again, if the thermometer is firmly fastened to the body, there is liable to be a local congestion, especially if the area of the thermometer is large, and the functions of the sweat glands, both underneath the thermometer and in its immediate vicinity, may be somewhat disturbed.

BASE-LINE IN MEASURING BODY-TEMPERATURE.

An examination of these different possibilities or localities for taking the temperature of the body shows immediately that those least affected by environmental changes are the natural cavities in the body, *i. e.*, the rectum, the vagina, and the mouth, the records obtained in the rectum being commonly considered the best suited as a base-line for all observations.

ERRORS IN RECTAL-TEMPERATURE MEASUREMENT.

In thus using the rectal-temperature as the base-line, it is necessary to take into consideration the possible errors affecting the measurements made in the

rectum. First, as has already been pointed out, the thermometer should not be inserted in the fecal mass. If there is any danger of this, the fecal matter should be removed by a water enema; also, sufficient time should elapse between the taking of the enema and the beginning of the temperature observations to make sure that the change in the local temperature produced by the water is not affecting the temperature of the rectum. Second, the thermometer must be inserted sufficiently deep to give the maximum temperature, the depth required being readily found by testing, and noting the point at which the maximum temperature occurs. If the thermometer is constructed of non-irritating material, there is very little liability of any local congestion. The experience of observers with glass mercurial thermometers has led to some difficulty in securing long-needed observations of body-temperature, owing to the rigid construction of the thermometers, but with the flexible thermometer employed by Benedict and Snell[1] continuous observations can be readily made in periods of several days, the thermometer being removed only for defecation. It seems well established, therefore, that with a proper construction of the thermometer the fear of local congestion may be entirely eliminated.

CONSTANCY OF RECTAL-TEMPERATURE.

If the rectal-temperature is to be used as the base-line, it is natural to assume that there should also be a more or less constant temperature which should be taken as the base-line, and we can properly question whether or not the rectal-temperature is sufficiently constant for this purpose. Obviously the temperatures which are markedly above the average of a large number of observations may be taken as indicating fever and should not be used as a base-line. On the other hand, there may be a fluctuation in the normal temperature amounting to 1.5° C., and any fluctuations within this limit may be reasonably taken as normal for the individual under experimentation. Before assuming that the observations of the rectal-temperature represent a normal value for the individual, however, we should examine carefully to find what factors affect the body-temperature.

FACTORS AFFECTING BODY-TEMPERATURE.

Exposure to severe cold lowers the temperature, provided there is no shivering incidental to an attempt on the part of the body to compensate for the excessive heat lost. The ingestion of hot or cold food and drink, likewise muscular work, produces an almost immediate effect. In connection with muscular work, it is important to note that there may be not only internal, but also external muscular work; consequently, for the strictest comparison, the temperature of the subject should be measured under constant conditions of muscular activity, ingestion of food, etc.

Furthermore, it has long been known among physiologists that there is a rhythm or periodicity in the temperature of the body. By experiment, it has

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[1]Benedict and Snell, Archiv f. d. ges. Physiol., 1901, 88, p. 492.

been found that this rhythm is somewhat as follows: The minimum temperature occurs during the early morning hours, usually between 2 and 5 o'clock; there is then a marked early morning rise which becomes less pronounced as the day progresses, but reaches its maximum in the afternoon about 5 o'clock; this is followed by a slight fall, which becomes very noticeable after retiring and gradually continues until the minimum point is again reached in the early morning.

A number of attempts have been made to explain this rhythm, which as yet have been only partially successful, although the rhythm appears to be more or less coincident with the muscular activity incidental to the day's work. This explanation is not scientifically complete, however, for it does not explain why a night watchman,[1] who for seven years had been working during the night and sleeping in the daytime, should still have the highest body-temperature at 4 or 5 o'clock in the afternoon when he was sound asleep, and the lowest value at 4 or 5 o'clock in the morning when he was awake and on his rounds. Daylight and cosmic influences have also been thought to have an effect upon this rhythm. It is not the object of this report, however, to enter into a discussion of the cause of the normal periodicity or rhythm, but in any study of body-temperature this factor should be taken into consideration when endeavoring to establish a base-line. For the particular reason for which this investigation was undertaken, namely, to study simultaneously the temperature fluctuations in different parts of the body in order to find whether or not they paralleled each other, the absolute temperature values at any given point are not of such great importance as are the variations. Consequently we may assume that previous experiments have demonstrated clearly the existence of a rhythm and have likewise demonstrated the difficulty of giving a satisfactory explanation which covers all observations thus far made.

Johansson's belief[2] that the body-temperature is influenced in large part by the metabolism is strongly substantiated by his observations, and yet it is difficult to conceive that the night watchman previously referred to had a higher metabolism during the periods when he was sound asleep than when he was sitting up in a chair engaged in conversation. From the well-known relationship between the pulse-rate and the metabolism, it is clear that all future experiments on body-temperature should be accompanied by a simultaneous observation of the pulse-rate and, so far as possible, of the metabolism and its changes. In the majority of experiments, observations of the metabolism will be impossible, but records of the pulse-rate may be easily obtained by practically all observers. If to these observations can be added others with regard to the blood pressure and pulse pressure, the results will be still more valuable, especially in throwing light upon the contention of Johansson that the body-temperature is a function of the total metabolism.

[1]Benedict, Am. Journ. Physiol., 1904, 11, p. 145.
[2]Johansson, Skand. Archiv f. Physiol., 1896, 7, p. 123.

PART II.—METHODS AND APPARATUS.

An analysis of the measurements to be made as outlined in the preceding section shows that the method of measurement must comply with the following requirements:

Several temperatures must be observed at practically the same time, and this process repeated at intervals of a few minutes for protracted periods.

The precision of the measurement must approximate 0.01° C.

The thermometers must be capable of being read without being disturbed; they must also be small and flexible, so as not to cause undue discomfort even if in position for a considerable length of time.

Only two methods were considered as being able to meet these conditions, namely, those employing (1) electrical resistance thermometers,[1] and (2) electrical thermal-junction thermometers.[2]

COMPARISON OF METHODS.

The many advantages of the resistance method have led to its extended application. In the first place, it has inherently a greater sensitiveness than can be obtained by the thermal-junction method. The reason for this might be suggested by the fact that in the resistance method the amount of energy expended in the thermometer is left entirely to the discretion of the designer, while in the thermal-junction method the source of energy is in the thermometer itself and therefore is limited by the physical properties of the junction. This implies, also, that the electromotive forces involved in the resistance method will, in general, be far greater than those used in measurement with the thermal junction, so that with the resistance method comparatively little trouble will be experienced from extraneous electromotive forces, which are so common a source of annoyance in thermo-electric measurements. Another advantage of the resistance method is that the measurement is completed by performing a single operation, usually that of balancing a bridge; there is no second temperature to be read, no potentiometer current to be adjusted, and no routine observations necessary to correct for the effect of extraneous electromotive forces. Also, the apparatus for measuring the temperature of the resistance thermometer is simpler than that required for the thermal junction, as in the former case no constant temperature need be maintained, also no standard cell is necessary.

In spite of these manifest advantages, there are certain qualities inherent in the resistance method which make it less fitted than the thermal-junction method for meeting the requirements previously outlined. For example, the measuring current flowing through the resistance thermometer produces an appreciable heating of the wire, the resistance of which is being measured. In measurements with the thermal junction, however, the current taken from

[1]Benedict and Snell, Archiv f. d. ges. Physiol., 1901, 88, p. 492; and 1902, 90, p. 33.
[2]Gamgee, Phil. Trans. Royal Soc. of London, Ser. B., 1908, 200, p. 219.

he junction for the purpose of deflecting a galvanometer would be very slight, so that the heating—which depends on the square of the current—would be very small indeed. Furthermore, a method may be used which does not involve drawing current from the junction, and thus the error may be entirely avoided.

Again, the resistance thermometer, as usually constructed for body-temperature measurement, consists of a coil of fine wire, inclosed in a metal shell. This construction is necessarily bulky, owing to the fact that a considerable quantity of wire must be used. Moreover, the mass of the thermometer is large, giving more or less lag, and its construction is relatively very difficult. The thermal-junction thermometer, on the other hand, in its simplest but thoroughly practical form, consists merely of a twisted and soldered joint between two fine wires, one of which is insulated, both wires being protected from moisture and mechanical injury by an outside case of thin-walled rubber tubing. It will thus be seen that the thermometer is small and flexible, which not only permits its ready introduction into the deep natural cavities of the body, but also allows it to be covered easily by flesh when used in the shallow artificial cavities; furthermore, its small mass precludes any appreciable lag.

A third disadvantage of the resistance method is that, in the type of thermometer commonly used for body-temperature measurement, the resistance itself is not in very good thermal contact with the body whose temperature is being taken, whereas the thermal connection between the thermal-junction thermometer and the body may be made absolutely ideal. Since no theoretical demands will be violated if one of the metals of the junction actually touches the body being measured, the junction may be made in the form of a wire of one of the metals soldered to the back of a thin plate or cap of the other and the face of this latter applied directly to the body; in this way the active material of the thermometer may touch the body without even the thinnest layer of isolating material.

A careful comparison of the advantages and disadvantages of these two methods, considered only in the light of the requirements of these special experiments and not at all with regard to temperature measurements in general, led to the adoption of the thermal-junction method, and this in spite of our previous extended use of the resistance thermometer for body-temperature measurements. The sensitiveness was considered ample, and the disadvantages of the occasional observations necessary in reading a second temperature, balancing current, and correcting for stray voltage were regarded as being more than offset by the freedom from heating and the ability to use thermometers which were at once small, simple, flexible, and strong. The thermal-junction method has the still further advantage that the thermometers are practically interchangeable without adjustment.

THEORY OF METHOD OF MEASUREMENT USED.

The thermal-junction method is based upon the well-known principle that if a junction of two dissimilar metals be heated, a difference of potential between the two will result; and if the circuit be closed through a galvanometer, a current will be produced and the galvanometer deflected. In order that small temperature fluctuations may be measured with precision, use is made of a second junction in series with and opposed to the first, this second junction being kept at a constant known temperature somewhere in the region of the temperature to be measured. By this means the net electromotive force is made very small, so that slight changes due to fluctuations of the unknown temperature form a large percentage of the whole. The use of deflections in this way, although convenient and simple, has one disadvantage, in that the resistance of the galvanometer and conducting wires must be taken into account, since a change in the circuit resistance would cause an inversely proportional change in the deflection. With the apparatus used in these body-temperature experiments, a fluctuation of more than 1.2° C. in the galvanometer temperature would not have been allowable. Moreover, the effective voltage at the galvanometer terminals, being the voltage of the thermal-junction system minus the fall in potential along the wires, would have been reduced to about 75 per cent of its total value.

These conditions, although not prohibitive, were nevertheless regarded as undesirable, so that a "null" method, by means of which they were entirely avoided, was finally decided upon. This "null" or "zero" method is a modification of the ordinary potentiometer method for the measurement of electromotive forces, and consists in balancing the electromotive force of the thermal-junction system against the fall in potential across a section

FIG. 1. Elementary wiring diagram of apparatus. Current from the battery B flows through the slide wire DC and returns to the battery through the ammeter A. The thermal-junction system TT, with the galvanometer G, is connected at one end to C, and at the other to a movable contact which may be touched at any point along the slide wire.

of a standardized slide wire in which a known current is maintained. An elementary diagram of connections is shown in fig. 1. The battery B sends a current through the circuit B-D-C-A-B, the value of the current being measured by the ammeter A. CD is a uniform slide wire of known resistance, to one end of which, as at C, is attached one end of the thermal-junction system TT. The other end of the thermal-junction system is connected through the galvanometer G to a movable contact which may be touched at various points along the slide wire until a point P is found at which no galvanometer deflection results. The voltage of the thermal-junction system can then be calculated, if desired, this being the product of the current expressed in amperes and the resistance CP expressed in ohms. The voltage of the system is, however, usually of secondary importance; what is desired is the tempera-

ture difference between the two junctions. This might be assumed to be approximately proportional to the voltage, but can be obtained directly by keeping both junctions at known temperatures; in this way the apparatus can be calibrated so that different settings of the contact correspond to definite values of the temperature difference being measured. In order to make the apparatus direct reading, an additional resistance in series with the battery is almost universally used and the current is so adjusted as to accommodate itself to the particular slide-wire available. By bringing the current to such a value that the fall in potential across one division of C-D is equal to the voltage of the thermal-junction system for a temperature difference of 0.01° C., the apparatus becomes practically direct reading in hundredths of a degree.

ADAPTATION OF METHOD FOR USE.

The actual arrangement, as shown in fig. 2 (p. 15), does not differ in principle from this. The storage battery B, which has been partly discharged in order to obtain a more nearly constant voltage, sends current continuously through the circuit $B-R-V_1-V_2-V_3-V_4-S$ in parallel with P-M-B. The resistance R is fixed, and is placed in the circuit for the purpose of bringing the current to such a value that the apparatus is practically direct reading; V_1, V_2, V_3, and V_4 are variable resistances by means of which the current can be maintained constant in spite of slight changes in the electromotive force of the storage cell, such as might be caused by a gradual discharging of the cell, temperature changes, etc. The shunt S is placed across the potentiometer P on account of the extremely low voltages to be measured. The resistance M is so arranged that the standard cell N and galvanometer G can be closed across it, this arrangement forming the equivalent of a very accurate ammeter, so precise that a high resistance O is introduced into its circuit to reduce the sensitiveness. Since the galvanometer must be used in connection with both the standard cell and the thermal-junction circuits, the switches G_1 and G_2 are provided for transferring it from one to the other. By means of the test switch T, the apparatus may be tested for stray electromotive forces. The control switch K is used for convenience in bringing the galvanometer to rest. The switches 1, 2, 3, 4, etc., are also provided so that the electromotive force of any one of a number of thermal-junction systems may be measured. To each of these switches are connected two copper wires, one of which runs to the body and the other to a constant-temperature bath, these latter terminals being connected by a constantan wire, which furnishes the second metal for the thermal junctions.

APPARATUS USED IN THE RESEARCH.

CONSTANTS OF THE APPARATUS.

While considering the measurement from a purely theoretical standpoint, and before proceeding to a description of the actual construction, it may be well to bring together the constants of such parts of the apparatus as were available for the work, and to include the computations by means of which

the remaining constants were derived and the suitability of the apparatus for the work assured.

The potentiometer has a resistance of 15,000 ohms, which can be included between the potential terminals in steps of 0.1 ohm. The galvanometer resistance is about 50 ohms, and the sensitiveness such that a deflection of 0.5 millimeter is produced by a current of 15×10^{-10} amperes. The resistance of the constantan wire as selected is about 14 ohms for each circuit; that of the copper is negligible. The electromotive force of the copper-constantan couple is taken as 40×10^{-6} volts per degree centigrade. The voltage of the storage cell is 2.0 volts, that of the standard cell 1.0197 volts. Most of the temperatures to be measured are assumed to lie within the limits of $36°$ to $38°$ C., and are desired to an accuracy of about $0.01°$ C. The apparatus, however, should not be restricted to these limits but should be capable of measuring lower temperatures, although with a somewhat decreased precision.

The constant-temperature junction is kept at a temperature of about $40°$ C., and as the other junction never rises to so high a temperature as this, it follows that the net voltage of the thermal-junction system always acts in one direction. The temperature difference between the junctions is usually not less than $2°$ C. nor greater than $4°$ C., so that under these circumstances the voltage limits would be 80×10^{-6} volts and 160×10^{-6} volts, between which the voltage should be determined to approximately 0.4×10^{-6} volts.

The necessity for a potentiometer shunt may be very easily shown. If the apparatus is to be direct reading—a change of 0.4×10^{-6} volts involving a change of 0.1 ohm in the potentiometer setting—then a current of (0.4×10^{-6}) $\div 0.1$, or 4×10^{-6} ampere is required, and this, if a regular series circuit is used, demands the use of a circuit resistance of $2 \div (4 \times 10^{-6})$ or 500,000 ohms. Since this is hardly practicable, it has been decided to shunt the potentiometer, leaving the current in the potentiometer itself 4×10^{-6} ampere, but taking from the storage battery about 0.01 ampere, and causing the remainder to flow through the shunt. For the main current a value of 0.0102 ampere has been decided upon, as this permits the use at M of a 100-ohm coil. The value of S is then $(4 \times 10^{-6} \times 15000) \div (0.0102) = 5.88$ ohms. The total resistance of the circuit is $2.0 \div 0.0102$ or 196 ohms, 100 ohms being taken by M and about 6 ohms by S in parallel with P, leaving still 90 ohms necessary to be taken up in R, V_1, V_2, V_3, and V_4.

To determine the proper value for each step of the variable resistances, it must be noted that while voltages as high as 160×10^{-6} volts are to be measured, yet a deviation of 0.2×10^{-6} volts will in itself produce an error in the results sufficient to affect the nearest hundredth of a degree. From this it is seen that the current must not vary by 2 parts in 1600, so that each step in the variable resistances must not make more than this fractional change in the resistance, or $(2 \div 1600) \times 196 = 0.25$ ohm. This represents the maximum allowable change; consequently the steps in the resistance as actually made are smaller than this. The smallest steps are in the resistance V_3, which is composed of nine 0.1 ohm coils. Similarly V_4 comprises nine 1.0 ohm coils, so

that the combination gives a resistance of about 10 ohms, variable in tenths of ohms. V_1 and V_2 are provided should even more adjustment be necessary, and have a resistance of 5 ohms each. This gives 20 ohms for the sum of the variable resistances, about half of which should be in circuit under normal conditions, so as to allow adjustment in either direction. The value for R is accordingly $90 - (20 \div 2) = 80$ ohms.

To determine whether the galvanometer is sufficiently sensitive, it will be simplest to consider the case of a measurement being made in which the circuit is not quite balanced, but owing to the insensitiveness of the galvanometer it appears to be so. The largest current that can pass through the galvanometer and still be undetected is 15×10^{-10} amperes. This current in flowing through a resistance of 64 ohms, composed of the galvanometer and thermal-junction system, causes a fall in potential of $15 \times 10^{-10} \times 64$ or about 10^{-7} volts. Since $0.01°$ C. corresponds to 0.4×10^{-6} volts, or 4×10^{-7} volts, it is seen that the error due to insensitiveness of the galvanometer corresponds to about $0.0025°$ C. and is therefore entirely negligible.

CONSTRUCTION OF THE APPARATUS.

Having determined the constants, or electrical dimensions, of the various pieces of apparatus considered in fig. 2, the actual method of construction and installation will be given in some detail. This seems advisable, since in some cases the peculiar experimental conditions to be met required a special form of construction; while in other cases some of the more elaborate pieces of apparatus available, which were not ideally adapted to the work, have been made to conform more closely to the desired qualifications.

MEASURING INSTRUMENTS.

Storage cell.—The storage cell B is one of a battery of six cells, having a normal rate of three-quarters of an ampere and provided with separate terminals for each individual cell. A suitable resistance, not shown in fig. 2, is arranged so that it can be connected across the battery when desired. The separate terminals permit each cell to be used singly, and the resistance is used partially to discharge the battery when freshly charged, thus causing its voltage to be more nearly constant.

Both the storage cell and the standard cell are provided with reversing switches, which are mounted on a single base and arranged so as to be operated together by means of one handle. This is done for the following reason: The electromotive force of the thermal-junction system, standard cell, and storage cell must all act so as to have a tendency to send current through the main circuit in the same direction. For the purpose of keeping the voltage set up by the junction unidirectional, the temperature of the oven is always kept higher than that of the body. In order to provide for a possible decrease in the oven temperature, with a consequent reversal of this voltage, the storage cell and standard cell are furnished with the reversing switches just mentioned.

The resistances R, V_1, V_2, V_3, V_4, S, M, and O, as well as the coils in the potentiometer, are of manganin. V_1 and V_2 are each arranged to be short-

circuited by knife switches, while V_3 and V_4 are made up from two dial switches. The wires joining the main circuit to the shunted potentiometer are connected to the terminals of the shunt rather than to the terminals of the potentiometer, since the resistance of the latter is very large as compared with the former.

Potentiometer.—The potentiometer used is a combined potentiometer and Wheatstone bridge, made by Wolff.[1] In this type of instrument, the resist-
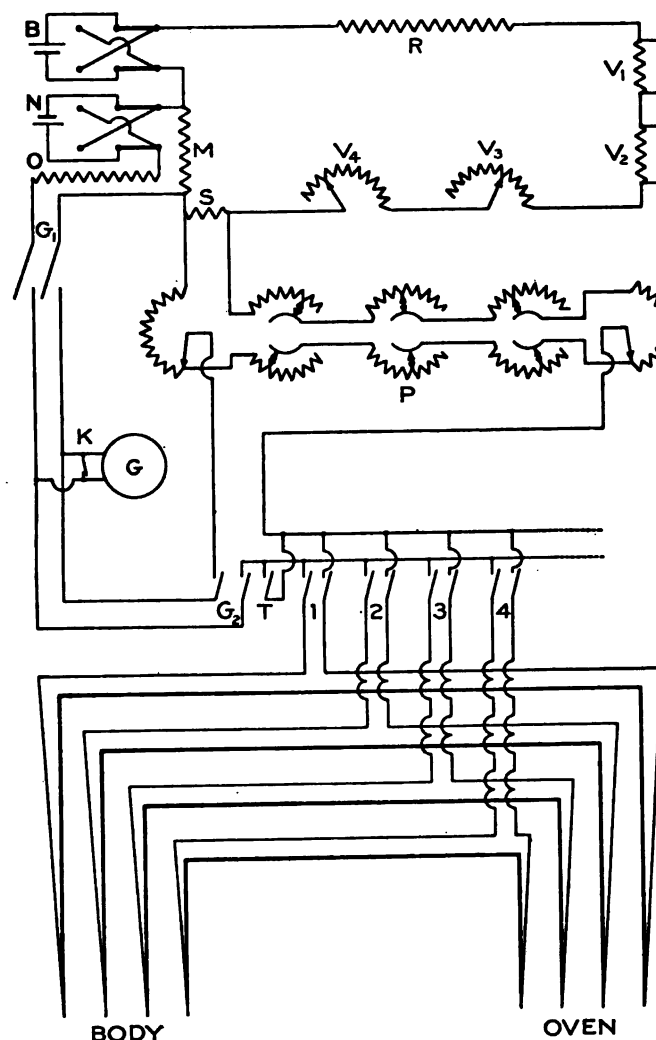
FIG. 2. Complete wiring diagram of apparatus. Current from the battery B flows through the resistances R, V_1, V_2, V_3, and V_4, and then divides, part flowing through the shunt S and part through the potentiometer P, the total current finally returning to B through the resistance M. The potentiometer, which is composed of 5 variable resistances is joined to the switching arrangement, of which G_1 connects the galvanometer G in circuit, T replaces the thermal-junction system when testing, and 1, 2, 3, 4, etc., are connected to the thermal-junctions at the body and the constant-temperature oven. The constantan wires are indicated by the heavy lines. N is the standard cell, protected by the high resistance O, and connected to the circuit through the double-contact key G_1. The switch K is for convenience in bringing the galvanometer to rest.

[1]Wolff, Zeitsch. f. Instrumentenkunde, 1903, Oktober.

ance is kept constant regardless of the position of the contacts by the device of two identical circuits, one of which is included between the sliding contacts while the other is not; these circuits being so arranged mechanically that as the resistance of one is decreased the resistance of the other is increased by the same amount. This arrangement has the disadvantage that contact resistance in the potentiometer circuit may affect not only the precision but also the accuracy of the measurement. In choosing apparatus for similar work, it should be noted that this is an unnecessary handicap, since the potentiometer may be so designed as not to require any contact in this very important part of the circuit. Also for thermo-electrical work, the potentiometer should have low resistance, so as to retain the full sensitiveness of the apparatus.

The potentiometer shunt is embedded in a block of paraffin, together with the brass binding posts of the potentiometer; also a similar block is used where the copper wires join the binding posts which are connected to the moving contacts. None of the knife switches G_2, T, 1, 2, 3, 4, etc., contain any junction of dissimilar metals, the circuit being copper throughout. Moreover, these switches are mounted at a distance of about 1 meter from the observer and are operated by means of long wooden rods. This construction is adopted in view of the fact that in some parts of the circuit, namely, in the potentiometer, the shunt, the switches just mentioned, the galvanometer, and the thermal-junction systems, it is very important to reduce as much as possible all stray electromotive forces.

The unavoidable junctions occur mostly in the form of reversed pairs; the paraffin blocks, by surrounding both these junctions with a medium having an appreciable mass, lessen the effect of transient fluctuations in the room temperature; furthermore, as these blocks have a greater heat-carrying capacity than air, they provide a better path for the transfer of heat between the two junctions, thus tending to equalize the temperature of the two. The slender wooden rods are used in connection with the switches as a further safeguard at these points to prevent heating from the hand.

Standard cell.—The resistance M is furnished in the usual way with both current- and potential-terminals. The standard cell N is a Weston Standard Cell, No. 1565, provided with the usual certificate stating its electromotive force. The following caution is expressed in the certificate: "To preserve the constancy of this cell, it should not be exposed to temperatures below 4° C., and no current greater than 0.0001 ampere should be passed through it." The insertion of the resistance O of 10,000 ohms assures the fulfilment of this latter requirement, and at the same time leaves an arrangement amply sensitive. The switch G_1 is in the form of a double-contact key, which remains open unless pressed, thus preventing the standard cell circuit from remaining closed accidentally.

Galvanometer.—The galvanometer is a reflecting instrument of the Deprez-d'Arsonval type, manufactured by Siemens & Halske. Among the advantages of this instrument might be mentioned first, that provision is made whereby

the whole moving system may easily be taken out and replaced by another, perhaps of different resistance or sensitiveness; second, that small windows are provided at the top and bottom of the suspension strip, by means of which it may easily be inspected or removed. The chief disadvantage for general work is, perhaps, that when the instrument is set up the moving coil is not visible and, the clearance being small, leveling becomes comparatively difficult. The resistance, 50 ohms, is rather too high for work of this character; probably a smaller resistance could have been used and still leave an instrument of sufficient sensitiveness. The galvanometer is not entirely free from thermal electromotive forces; indeed, this could hardly be the case where a number of metals are in circuit. This disturbing effect has been found to be less, however, in an instrument purchased in 1907 than in a later model purchased in 1909. With a view toward reducing extraneous electromotive forces in the galvanometer, it has been shielded as much as possible from temperature changes by placing over it a cork-lined wooden box. This is provided with a door at the side for inspection, leveling, etc., and with a transparent celluloid window in front through which the rays of light can pass. Since the use of a telescope for reading was regarded as too tiring for repeated observations, a ground-glass scale at a distance of almost 4 meters has been used, upon which the reflection of the filament of an incandescent lamp is focussed. If too long a scale distance should be used, in the attempt to increase the sensitiveness, a blurred image will result, caused by slight imperfections in the surface of the mirror.

The galvanometer has been mounted in the following way: A location was chosen near a structural steel upright on the street floor of the building and a strong shelf built out from the wall at this point. Upon the shelf was placed a square block of cork, 3 or 4 cm. thick, to which was fastened a 1.25 centimeter iron plate, and on this the galvanometer was mounted. The very slight vibration of the shelf resulting from the jar of the building is damped out by the cork, which acts as a spring.

The copper wires running to the thermal junctions have a diameter of 1.63 millimeters up to within 1 or 2 meters from the junction itself. At this point they are joined to smaller copper wires (0.455 millimeter), thus making the junctions smaller and more flexible. The wiring should be done in such a way as to leave no avoidable loops in the circuit; this will eliminate the inductive action of neighboring circuits, which otherwise might cause annoying deflections of the galvanometer.

THERMAL-JUNCTION SYSTEM.

Thermometers for internal temperatures.—Most of the junctions used for measuring temperature in the natural and artificial cavities of the body are simply twisted and soldered joints between two wires—one of constantan (0.455 millimeter) and the other of copper (0.455 millimeter). For taking internal temperatures a construction like A (fig. 3) is employed, in which the two wires run side by side, one of them being inclosed in a rubber tube for

insulation. The wires are then twisted and soldered together in the usual way, tied with silk, and finally covered with thin pure gum tubing. Before insulating the bare copper wire, however, the precaution is taken to protect it from the corrosive action of the sulphur in the rubber by "tinning" it or covering it with solder. It was found that the lag of the thermometer, due to the rubber tubing, was about 2.5 minutes;[1] this was regarded as being not too great.

For taking temperatures in the axilla a thermometer of the type illustrated under B, fig. 3, recommends itself. Here the joint is made by twisting and soldering two wires which approach each other from opposite directions, the inclosure in tubing being the same as before.

Another type of thermometer is shown in C, fig. 3. Here one of the metals of the junction touches the body without the intervention of any isolating material, so that the conditions for the taking up of the temperature by the thermometer are ideal. The copper element is made in the form of a very
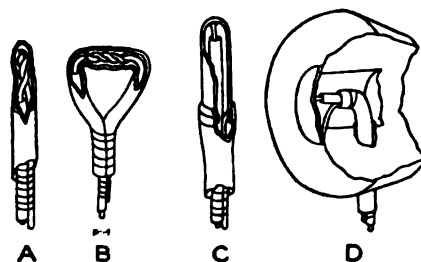
Fig. 3. Types of thermal-junction thermometers used. A, junction inclosed in rubber tube, used principally for internal measurements; B, same, arranged for use in axilla; C, junction in which one metal touches body, for taking internal temperatures; D, modification of this type for surface measurements.

thin hollow thimble, to the inside of which, at the end, is soldered the constantan wire, properly insulated. A copper wire soldered to the thimble completes the circuit. The connecting wires and the open end of the cap are covered by rubber tubing, and tied with silk, after which the copper is silver-plated. This arrangement fulfils the theoretical condition that both elements should not touch the skin, and at the same time provides an excellent thermal relation between the thermometer and the body whose temperature is being measured.

Thermometers for surface temperature.—The attempts made to obtain accurate measurements of the surface temperature were not successful, but a brief description of the thermometers used may be of interest. Several types of skin thermometers were constructed. At first the ordinary rubber-covered

[1]The method of testing the thermal-junction thermometers for lag was as follows: The thermometer being tested was connected to the measuring circuit and suddenly thrust into a flask of water at about body temperature. This caused a galvanometer deflection which at first changed rapidly but gradually became more nearly constant and finally could not be observed to change at all, the change in deflection corresponding to the change in temperature of the junction. The length of time noted above (2.5 minutes) is the interval elapsing from the instant when the thermometer was immersed until the deflection had become constant.

thermometers, A or B, fig. 3, were used, these being held in place by a bandage; afterwards they were pressed somewhat into the flesh by placing them under small pieces of wood which were strapped in position. A later type is shown in D, fig. 3. Here the general shape of the thermometer is along the lines finally used by Gamgee.[1] The support consists of a cork disk, somewhat rounded on the face. To this is shellacked a piece of thin sheet copper, shaped
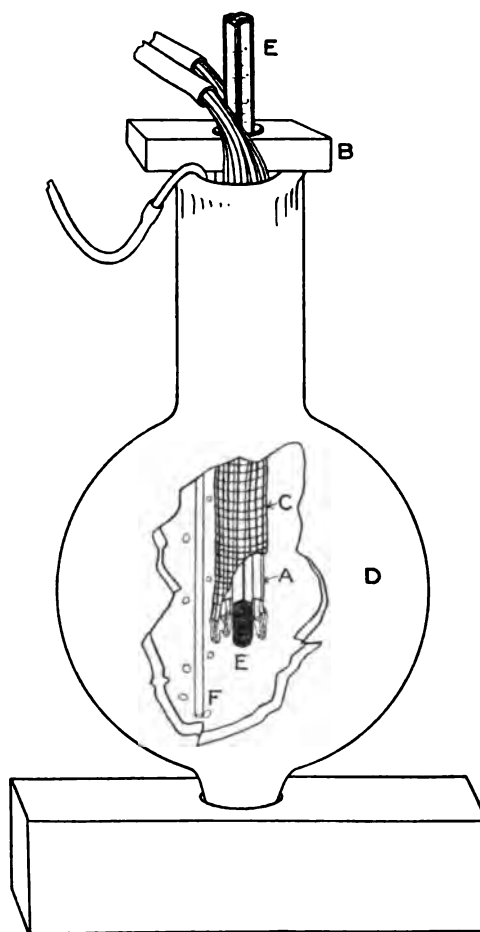
- 10. 4. Details of constant-temperature bath. The tube A, mounted in the block B, and inserted in a bath of warm water in the Dewar flask D, serves as a support for the thermal-junction wires C. The mercury thermometer E is inserted to the depth of the thermal-junctions. The water in the flask is stirred by compressed air entering through the tube F.

so as to bulge outward from the support. This copper plate furnishes one of the metals of the thermo-couple, a constantan wire soldered to the center of the back supplying the other, and a copper wire, also soldered to the plate, completing the circuit. The base is made of cork in order to give the apparatus a smaller mass, and the copper is shaped in the manner described so that it may

[1]Gamgee, loc. cit.

press into the flesh and take up the deeper temperature. The thermometer is held in place by a cloth strap. The junction itself must be shielded so that it may take up the body-temperature, and yet this must not interfere with the natural liberation of heat. These two conditions are incompatible, but the shape of thermometer chosen seems to fulfil both as well as possible.

Thermal junctions used in the constant-temperature bath.—The thermal junctions used in the constant-temperature bath are all made in the same way. The two small wires are slipped into separate capillary rubber tubes and a soldered joint made exactly as in type A (fig. 3) previously described. The different junctions are then supported in the following manner: A piece of glass tubing (A, fig. 4) is used, about 15 centimeters long and having a 16 millimeter bore. The upper end of this tube is passed through a block of wood B and secured with silk and shellac. Along the outside walls of the tube the thermal-junction wires C are laid, and firmly tied with silk in such a way as to leave the junctions protruding 1 or 2 centimeters from the bottom of the tube. The ends of the junctions are carefully separated, and the whole arrangement dipped in paraffin. The paraffined junctions, together with the glass tube, are then immersed in water contained in a large spherical Dewar vacuum flask D with silvered-glass, double walls. This flask has an outside diameter of about 15 centimeters, the distance between the walls being 8 millimeters, the length of the neck approximately 10 centimeters, and the capacity 1100 cubic centimeters.

A mercury thermometer, E, which indicates the temperature of the bath, passes through the tube A to such a depth that its bulb lies very near the thermal junctions and at the same level. This construction allows the thermometer to take up the temperature of the junctions very closely. The mercury thermometer is of the Beckmann type, having a range of 5° C., is graduated in hundredths of a degree, and calibrated by the Physikalisch-Technische Reichsanstalt. The true temperature, as obtained from the reading of such a thermometer, would be expressed by the formula $T = A + KR$, where T is the temperature desired, A being the zero reading of the thermometer, K a calibration constant which equals the true value of a scale division for the particular conditions of use, and R the reading.

CONSTANT-TEMPERATURE OVEN.

The flask D is placed in an oven, F (see fig. 5), in which the air is maintained at a constant temperature by the use of a mercury thermostat G which automatically supplies the proper amount of gas to a small burner H located beneath the oven. This oven, which is of sheet metal and about 33×40×50 centimeters, is inclosed in a slightly larger asbestos case with a sheet-metal bottom, the air space between the oven and the outside case being about 25 millimeters. The fronts of both are hinged; in the top are three holes, one for the insertion of the thermostat, one for the mercury thermometer E, and one for the insertion of the wires of the thermal-junction system. Through the last opening is also inserted a mercury thermometer for indicating roughly the

temperature of the air in the oven, and a tube for compressed air. By means of this tube compressed air, which has previously been passed through an indicator outside of the oven, is conducted into a bottle of water placed in the oven, and finally passes in a succession of bubbles up through the water in the Dewar flask itself.

By automatically keeping the air in the oven at the same temperature as the water in the flask, any small heat loss from the flask is avoided. The outer air-space and asbestos casing also aid in the temperature control of the oven, while the metal bottom assists in the equalization of the heat from the burner.

It was at first thought that, with the flask surrounded by ideal conditions,
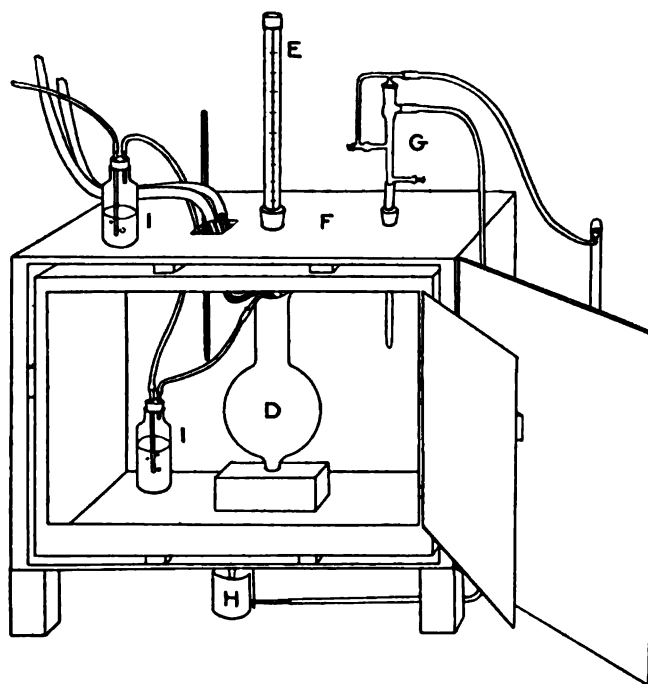
Fig. 5. Constant-temperature oven. Inside the oven F, in the center, is shown the constant-tempera-
ture flask D, with the mercury thermometer E. On the right is the thermostat G which
supplies gas to the burner H below the oven; at the left is the arrangement I I supplying com-
pressed air for stirring the water in the flask D.

sufficient stratification could hardly exist to produce a sensible error in the reading. It was found, however, that appreciable temperature differences did exist in the flask and, although the thermometer bulb and thermal junctions were all at the same level, it was considered advisable to provide some method of stirring. For this reason, compressed air was introduced, being selected as a convenient method for stirring the bath, especially in view of the fact that the space available was small. By passing the air first through a vessel of water inside the oven it is brought to the temperature of the water in the flask and, still more important, is saturated with moisture at the same tempera-ture, so that no heat is lost either by absorption or by evaporation.

To prevent cooling by evaporation from the surface, the water in the flask was at first covered by a thin film of oil; but this necessitated such an elaborate arrangement to protect the rubber tubing that the oil is now omitted, with equally satisfactory results. The performance of the constant-tempurature oven has proved very satisfactory, the temperature within the flask frequently not changing more than 0.01° C. in an hour.

CALIBRATION OF MERCURY THERMOMETERS.

The following is an abstract of the calibrations of the various thermometers used in the work, as given by the Physikalisch-Technische Reichsanstalt. In the case of the Beckmann thermometers, data are given showing how the constant K, previously mentioned,[1] is determined. The tables of corrections for variations in caliber have been omitted in the Beckmann calibrations, but a statement is made regarding the maximum value of the correction.

Beckmann Thermometer PTR 40724.

Range.	Average temperature of exposed stem.	Value of scale division Jena glass 16^{111}.	Correction.	Corrected value of scale division.
°C.	°C.			
30–35	22	1.013	−0.008	1.005
40–45	24	1.017	−0.008	1.009

Since the thermometer is to be used at temperatures of 37° to 42° C., an interpolation has been made in the above table, giving as the corrected value of a scale division,

$$1.005 + [(37 - 30) \div (40 - 30)] \ (1.009 - 1.005) = 1.008$$

No caliber correction greater than 0.005° C. is given, so that for readings only to 0.01° C., this correction is negligible.

Beckmann Thermometer PTR 40723.

Range.	Average temperature of exposed stem.	Value of scale division Jena glass 16^{111}.	Correction.	Corrected value of scale division.
°C.	°C.			
30–35	22	1.013	−0.006	1.007
40–45	24	1.017	−0.006	1.011

This thermometer is to be used in calibrating at temperatures of 34° to 39° C. The corrected value of a scale division is therefore:

$$1.007 + [(34 - 30) \div (40 - 30)] \ (1.011 - 1.007) = 1.009$$

No caliber correction greater than 0.005° C. is given.

Richter Thermometer PTR 32689.

Range 34°–44° C., graduated in 0.01° C. Without sensible error throughout, *i. e.*, no correction so great as 0.005° C.

In calibrating a Beckmann thermometer in this laboratory, its zero point was determined roughly, and then the thermometer was set by trial until the

desired value was approximately obtained. A careful determination was then made by tying the Beckmann and Richter thermometers together and immersing the pair in a Dewar flask similar to that used in the constant-temperature oven. The flask was filled with warm water stirred by compressed air, and immersed in a large body of hot water in an outside pail, the temperature of this outside water being regulated by an electric-coil heater. This heater is simply a resistance wire inclosed in a water-tight spiral tube, having in its outside electrical circuit a variable resistance, so that the amount of heating can be controlled. Several simultaneous readings of the thermometers were taken, as shown by the data given in table 1 which represent the determination of the zero point of Beckmann thermometer 40724, used in the constant-temperature oven. The Beckmann reading, corrected for caliber errors, must be multiplied by 1.008—the constant determined from the above calibration—and subtracted from the true temperature in order to give the zero point of the thermometer.

TABLE 1.—*Determination of zero point, Beckmann thermometer PTR* 40724.

Richter thermometer 32689 reading.	Beckmann thermometer 40724.		Corrected reading multiplied by 1.008.	Zero point of Beckmann thermometer.	Deviation from av.
	Reading.	Corrected reading.			
39.04	1.735	1.731	1.75	37.29	0.010
39.04	1.735	1.731	1.74	37.30	.000
39.04	1.732	1.728	1.74	37.30	.000
39.04	1.728	1.724	1.74	37.30	.000
39.04	1.726	1.722	1.74	37.30	.000
39.04	1.725	1.721	1.73	37.31	.010
39.02	1.712	1.708	1.72	37.30	.000
39.01	1.702	1.698	1.71	37.30	.000
				Av. = 37.300	0.003

Thus the correct temperature as determined from a reading of this thermometer is given by the formula $37.300 + 1.008 \times$ reading. When working only to hundredths, the formula $37.30 + 1.01 \times$ reading gives closer results at the lower part of the scale, but $37.29 + 1.01 \times$ reading is better on higher readings.

METHOD OF OPERATING APPARATUS.

In measuring temperatures with this apparatus the procedure is first to connect the partly discharged cell to the measuring circuit for a few minutes in order to let the current become constant, and then carefully to depress the key G_1. In general, a galvanometer deflection results, indicating that the current differs from its standard value. By regulating the variables V_3 and V_4, and also, if necessary, V_1 and V_2, this deflection is brought as nearly as possible to zero, thus indicating that the current has closely enough its proper value. The current having been adjusted, the next step is to close G_2 and one of the switches 1, 2, 3, 4, etc., according to which thermal junction is to be used. In general a deflection results, which can be almost balanced by properly moving the potentiometer contacts. The attempt is not made to

balance exactly, as this requires some time, but after the balance has been obtained within perhaps 0.1° C., the potentiometer setting and the deflection are observed and noted. From time to time the current is checked as at the beginning, also the temperature of the constant-temperature bath is occasionally taken and the correction for extraneous electromotive force determined. For the purpose of making this last test the test switch T is provided. The connections are such that if this switch is closed, instead of one of the switches 1, 2, 3, 4, etc., the apparatus is in the condition usual for a temperature measurement, except that the thermal-junction system is replaced by a direct copper connection. The electromotive force in this circuit should then be zero, and if the potentiometer is set at zero, a balance should be obtained. If this is not the case, a galvanometer deflection will result, indicating the presence of an extraneous electromotive force. This error may be determined either by changing the potentiometer setting until a balance is obtained, or else—having a knowledge of the sensitiveness of the galvanometer—by interpreting it directly from the deflection. The latter method, being quicker, is perhaps preferable; it also frequently saves reversing the storage cell and standard cell, which would be necessary in balancing if the stray electromotive force happens to oppose the main voltage of the thermal-junction system.

CALIBRATION OF THERMAL JUNCTIONS.

In calibrating the thermal junctions, a Dewar flask was used, similar to that in the constant-temperature oven. This was filled with water at about body-temperature and immersed in a considerable mass of warm water in a pail, the temperature of the outside water being controlled by an electric-coil heater. The Beckmann thermometer (40723), already described, and all the junctions to be calibrated were placed side by side and bound together with rubber bands in such a way as to bring the junctions at about the middle of the bulb, but without pressure on the bulb itself. The thermometer and junctions were then inserted in the calibrating flask, the surrounding water being stirred by compressed air from the supply in the constant-temperature oven. After the temperature in the calibrating flask had become constant the Beckmann thermometer was read, the necessary potentiometer readings were made for each thermal junction, and the reading of the Beckmann thermometer in the constant-temperature oven was taken. Usually four complete series of readings were made as quickly as possible; their average furnished data which showed the relation between temperature difference and potentiometer balance for this point.. After this another temperature was used in the calibrating flask and similar data obtained. In this way the junctions were calibrated throughout the range of temperature difference likely to occur in an actual experiment.[1]

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[1]These conditions are also suitable for testing the constantan wire for inhomogeneity. The most important part of the circuit, namely, that where the temperature gradient is usually steepest and most variable, occurs near the junction for use on the body. This region may be explored by keeping the junction at a fixed temperature in the bath, meantime immersing the wires to varying depths. A number of tests made in this way showed no change in the galvanometer deflection, indicating that the wire was sufficiently homogeneous for this work.

Part of an actual calibration will serve to show the nature of the results obtained. After the preliminary adjustment of the current the following data were taken: First, the temperature in the flask, then as quickly as possible the potentiometer readings for the junctions A, B, C, D, E, F, and G. It might be remarked that the potentiometer setting was kept fixed throughout and the deflections noted; this saved a great deal of time. These were quickly followed by a second reading of the temperature in the flask, and also a reading of the temperature in the constant oven. Finally the stray electromotive force was measured and the current balanced as before. Then the series of observations was immediately repeated. The mercury thermometers were read to 0.002° C., and the deflections to the nearest half millimeter. The data are given in table 2.

TABLE 2.—*Calibration of thermal junctions, February* 1, 1911.

Initial temperature in flask..	3.774		3.770		3.775		3.745		*Averages* 3.761	
	Setting.	Defl.	Setting.	Defl.	Setting.	Defl.	Setting.	Defl.	Setting	Defl.
Potentiometer readings:	*ohms*	*mm.*	*ohms*	*mm.*	*ohms*	*mm.*	*ohms*	*mm.*	*ohms*	*mm.*
Junction A...	18.00	±0.0	18.00	−1.5	18.00	−4.0	18.00	−5.5	18.00	−2.7
Junction B...	18.00	+5.0	18.00	+4.0	18.00	+1.5	18.00	±0.0	18.00	+2.6
Junction C...	18.00	+7.5	18.00	+6.0	18.00	+3.5	18.00	+2.5	18.00	+4.9
Junction D...	18.00	+5.0	18.00	+4.0	18.00	+2.0	18.00	±0.0	18.00	+2.7
Junction E...	18.00	+2.5	18.00	+1.0	18.00	−0.5	18.00	−2.5	18.00	+0.1
Junction F...	18.00	+7.0	18.00	+6.0	18.00	+4.0	18.00	+2.5	18.00	+4.9
Junction G...	18.00	+7.0	18.00	+6.0	18.00	+4.0	18.00	+2.0	18.00	+4.8
Final temperature in flask.	3.774		3.770		3.775		3.740		3.760	
Temperature in oven......	2.458		2.458		2.459		2.459		2.459	
Stray deflection........	+3.0 mm.		+2.5 mm.		+3.0 mm.		+4.0 mm.		+3.1 mm.	
Current balance[1].......	6.8 ohms		6.7 ohms		6.6 ohms		6.6 ohms		....	

[1]Not used in computations. The figure given is the reading of the variable resistance when the current is balanced.

COMPUTATIONS FOR THE CALIBRATION.

The corrected potentiometer balance differs from the setting in two respects: (1) correction for stray electromotive force must be made, and (2) since the balance consists partly of a setting and partly of a deflection, the effect of this deflection must be included.

The correction for stray electromotive force is obtained in direction and amount by consideration of the following facts: The galvanometer connections are such that a positive deflection requires a decrease in the potentiometer setting to bring it to 0; therefore, a positive stray deflection, such as is seen in table 2, by demanding a further decrease in the potentiometer setting, which is already 0, indicates a stray electromotive force opposite in direction to the net electromotive force of the thermal-junction system. Hence, the

potentiometer setting would have been greater had it not been for the presence of this extraneous electromotive force, and so the correction must be added. The actual magnitude of the stray correction is determined from the galvanometer sensitiveness and the average stray deflection. The sensitiveness of the galvanometer has been found by trial to be such that when taking the stray correction—which necessitates setting the potentiometer at 0—a deflection of 25 millimeters corresponds to a change in the potentiometer setting of 1 ohm, so that a deflection of 1 millimeter corresponds to a change in setting of $1 \div 25$ or 0.040 ohm. The average stray deflection in the calibration just given is 3.1 millimeters. This, it is seen, is equivalent to a change in setting of 0.040×3.1 or 0.12 ohm, which is therefore the correction that must be added to the setting on account of the stray electromotive force.

When taking the readings of the thermal junctions, the potentiometer setting is no longer 0, but is increased in the present instance to 18 ohms. This change increases the resistance of the galvanometer circuit and thus reduces its sensitiveness, so that under the new conditions a deflection of 1 millimeter has been found by trial to correspond to a change in setting of 0.063 ohm. As before, a positive deflection is equivalent to a decreased balance. Thus, the final corrected balances for the different junctions are:

$$A, 18.00 + 0.12 + 2.7 \times 0.063 = 18.29$$
$$B, 18.00 + 0.12 - 2.6 \times 0.063 = 17.96$$
$$C, 18.00 + 0.12 - 4.9 \times 0.063 = 17.81$$
$$D, 18.00 + 0.12 - 2.7 \times 0.063 = 17.95$$
$$E, 18.00 + 0.12 - 0.1 \times 0.063 = 18.11$$
$$F, 18.00 + 0.12 - 4.9 \times 0.063 = 17.81$$
$$G, 18.00 + 0.12 - 4.8 \times 0.063 = 17.82$$

The temperature difference is determined from the average readings of the two Beckmann thermometers, one in the constant-temperature oven, the other in the calibrating flask. The temperature in the constant-temperature oven is given by the formula previously deduced:[1]

$$\text{Temperature in oven} = 37.300 + 1.008 \times \text{reading}$$
$$= 37.300 + 1.008 \times 2.459 = 39.779° \text{ C.}$$

Similarly the temperature in the calibrating flask is given by the formula:

$$\text{Temperature in flask} = 34.365 + 1.009 \times \text{reading}$$
$$= 34.365 + 1.009 \times 3.761 = 38.160° \text{ C.}$$

The temperature difference is then:

$$39.779 - 38.160 = 1.619° \text{ C.}$$

The potentiometer balance corresponding to a certain temperature difference has now been obtained for each of the several thermal junctions, and this temperature difference accurately determined by means of the two mercury thermometers. A knowledge of the relation between these two quantities (1) potentiometer balance and (2) temperature difference, is the sole object of calibrating. This relation was determined for a number of temperature differences and the results expressed in a number of curves, one for each junction. These curves are very nearly straight lines for the range and pre-

cision used. Slight differences will be noted among the several junctions in the calibrations given. These are not due to experimental error, as the figures reproduce themselves very well; the cause is probably to be found in a slight inhomogeneity of the constantan wire at the different junctions. In actual experimenting the potentiometer balance is obtained, and by means of the calibration curves just described the corresponding value of the temperature difference can at once be found.

A SAMPLE BODY-TEMPERATURE EXPERIMENT.

In an experiment the junctions are placed at the different points where it is desired to obtain the temperature, being held in position when necessary by a strap or bandage. The apparatus is then operated in the manner previously described, so as to obtain data for computing the temperatures at the various points every 5 or 10 minutes, as the rate of temperature change seems to require. A few observations from an actual experiment are given in table 3, in which are noted: First, the time; next, an occasional balancing of the current; then the potentiometer readings for the various junctions, each reading consisting of a setting and a deflection as already described. After these follows an occasional reading of the Beckmann thermometer in the constant-temperature oven. Finally a column is provided for miscellaneous remarks, including observations for extraneous electromotive force, etc.

TABLE 3.—*Body-temperature experiment.*

Date: March 1, 1911. Subject: C. H. H.

Time.	Current balance.	Potentiometer readings.								Constant oven-temperature reading.	Notes.
		Junction A, Deep[1] rectum.		Junction B, Shallow[2] rectum.		Junction C, Left axilla.		Junction D, Mouth.			
		Setting.	Defl.	Setting.	Defl.	Setting.	Defl.	Setting.	Defl.		
P. M.	ohms	ohms	mm.	ohms	mm.	ohms	mm.	ohms	mm.		
1ʰ11ᵐ	....	34.0	−2	34.0	−3	37.0	+1	37.0	+6	3.07	Stray
16	1.1	34.0	±0	34.0	−3	37.0	+3	36.0	+5	......	defl. =
21	....	34.0	+1	34.0	−1	37.0	+8	35.0	−4	......	+2 mm.
26	....	34.0	+3	34.0	±0	36.0	−3	35.0	−2	......	

[1] Junction about 11 cm. deep in the rectum.　[2] Junction about 7.5 cm. deep in the rectum.

COMPUTATIONS FOR THE EXPERIMENT.

The method of obtaining the temperatures at the different locations and times specified involves very much the same type of computation as that used in calibrating.[1] The corrected potentiometer balance is obtained exactly as in the calibration computations by adding two quantities to the setting: First, the correction for extraneous electromotive force; and second, the deflection which has been multiplied by a factor depending on the galvanometer sensi-

tiveness. Having determined the corrected potentiometer balance, the temperature difference between the two junctions is found at once by reference to the calibration curves, where the relation between these two quantities is shown. The oven-temperature is computed to the nearest hundredth from the reading of the Beckmann thermometer. The body-temperature in any particular case is then found by subtracting the temperature difference from the temperature in the constant oven. The computations by means of which the various temperatures in the foregoing sample experiment were obtained are given in table 4.

TABLE 4.—*Computations for the experiment.*

Date: March 1, 1911. Subject: C. H. H.

Time.	Corrected potentiometer balance.	
	A	B
P. M.	*ohms*	*ohms*
1ʰ11ᵐ	34.0+2×.04+2×.08=34.2	34.0+2×.04+3×.08=34.3
16	34.0+2×.04+0 =34.1	34.0+2×.04+3×.08=34.3
21	34.0+2×.04−1×.08=34.0	34.0+2×.04+1×.08=34.2
26	34.0+2×.04−3×.08=33.9	34.0+2×.04+0 =34.1
	C	D
	ohms	*ohms*
1ʰ11ᵐ	37.0+2×.04−1×.08=37.0	37.0+2×.04−6×.08=36.6
16	37.0+2×.04−3×.08=36.8	36.0+2×.04−5×.08=35.7
21	37.0+2×.04−8×.08=36.4	35.0+2×.04+4×.08=35.4
26	36.0+2×.04+3×.08=36.3	35.0+2×.04+2×.08=35.2

Time.	Temperature difference (from curves).				Oven-temperature.	Body-temperature.			
	A	B	C	D		A Deep rectum.	B Shallow rectum.	C Left axilla.	D Mouth.
P. M.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
1ʰ11ᵐ	3.13	3.16	3.43	3.38	37.29+1.01×3.07	37.26	37.23	36.96	37.01
16	3.12	3.16	3.41	3.30	=40.39	37.27	37.23	36.98	37.09
21	3.11	3.15	3.38	3.27	....	37.28	37.24	37.01	37.12
26	3.10	3.14	3.37	3.25	....	37.29	37.25	37.02	37.14

PRECISION OF MEASUREMENT.

To meet the approximate demands of a precision discussion, the potentiometer balance may be assumed as directly proportional to the temperature difference between the hot and cold thermal junctions; hence the relation between the two can be expressed by a single factor, rather than by a curve. An approximate value of this factor, by which the potentiometer balance should be multiplied to give the temperature difference, is 0.094.

The body-temperature would then be expressed by the formula:

$$Tu = T_0 - BF$$

in which

Tu = unknown temperature
T_0 = oven-temperature
B = potentiometer balance
F = factor showing relation between potentiometer balance and temperature difference.

Assume in an average case: $T_0 = 40°$ C., $B = 32$, and $F = 0.094$. This will give for Tu a value of $40 - 0.094 \times 32 = 37°$ C.

The precision of the various factors is determined as follows: T_0 is the oven temperature as read during the course of an experiment, and has been shown in a previous paragraph to be expressed by the formula:

$$T_0 = A + KR$$

where

A = zero point of thermometer, which has been determined to at least $0.01°$ C.
K = 1.01 = constant
R = reading, taken to the nearest $0.01°$ C.

B, the potentiometer balance, is determined in the last place by deflection, which is read to the nearest half-division. The sensitiveness of the galvanometer in this case is such that a deflection of 1 division corresponds to a change in B of 0.072 ohm. Hence the average deviation in B is 0.036 ohm.

F is obtained by calibration. In calibrating, the following data are obtained: To_1, the oven temperature, which may be taken as $40°$ C.; Tf_1, the temperature in the calibrating flask, for instance, $37°$ C.; and B_1, the potentiometer balance, 32. From these the quantity $F = (To_1 - Tf_2) \div B_1$ is computed. In calibrating, the temperatures are taken more precisely than in an experiment, and this involves not only a closer reading, but a better determination of the zero point of the thermometers. As a matter of fact the reading is taken to $0.002°$ C.; and the zero known to $0.003°$ C. Therefore we may say, similarly to the above, $To_1 = A' + K'R'$ and $Tf_1 = A'' + K''R''$, where A' and A'' are known to $0.003°$C.; K' and K'' are constants; and R' and R'' are known to $0.002°$C. B_1, like B, is known to 0.036.

The complete expression for the unknown temperature is then as follows:

$$Tu = A + KR - B \frac{(A' + K'R') - (A'' + K''R'')}{B_1}$$

The average deviations of the variables are:

A, a.d. $= 0.01$; R, a.d. $= 0.01$; B, a.d. $= 0.036$; A', a.d. $= 0.003$;
R', a.d. $= 0.002$; A'', a.d. $= 0.003$; R'', a.d. $= 0.002$; B_1, a.d. $= 0.036$.

The constants K, K', and K'' each have the value 1.01.

The effect on the final result of the deviation in each component is obtained by the aid of the differential calculus. Adopting the usual notation:

$$\Delta A = 0.01 \qquad\qquad\qquad \Delta R = K \times 0.01 = 0.01$$

$$\Delta B = \frac{(A' + K'R') - (A'' + K''R'')}{B_1} \times 0.036 = \frac{3}{32} \times 0.036 = 0.0034$$

$$\Delta A' = \frac{B}{B_1} \times 0.003 = 0.003 \qquad\qquad \Delta R' = \frac{BK'}{B_1} \times 0.002 = 0.002$$

$$\Delta A'' = \frac{B}{B_1} \times 0.003 = 0.003 \qquad\qquad \Delta R'' = \frac{BK''}{B_1} \times 0.002 = 0.002$$

$$\Delta B_1 = \frac{B[(A' + K'R') - (A'' + K''R'')]}{(B_1)^2} \times 0.036 = \frac{3}{32} \times 0.036 = 0.0034$$

The deviation in the final result will then be

$$\Delta = \sqrt{(.01)^2 + (.01)^2 + (.0034)^2 + (.003)^2 + (.002)^2 + (.003)^2 + (.002)^2 + (.0034)^2}$$
$$= 0.016° \text{ C}.$$

It is thus seen that the deviation expected in the body-temperature, caused by the deviations in the various components, is 0.016° C.; that is, each temperature is measured to 0.01° or 0.02° C. It should be remembered, moreover, that the primary object of this study is to determine the temperature differences between different points of the body rather than the absolute temperatures. A number of circumstances can be conceived which might cause an error in the absolute determination of temperature, but which would be without effect on the difference between two temperatures. The results stated therefore are regarded as singularly good.

LATER MODIFICATION OF THE APPARATUS.

After the conclusion of this research, it was desired to extend the application of the apparatus to the determination of the rectal temperatures of subjects in the respiration calorimeters installed in this laboratory. It was thought undesirable, however, to reserve the Wolff potentiometer for this special work, as to do so would preclude its being used for any other measurements; therefore a special potentiometer for body-temperature measurements has been constructed. The circuit arrangement of this instrument is somewhat different from the ordinary potentiometer, and was suggested informally to one of the writers by Dr. Walter P. White, of the Geophysical Laboratory of the Carnegie Institution of Washington in Washington, D. C. It is a pleasure here to acknowledge our indebtedness to Dr. White, whose unusual experience with thermal junctions made his suggestions doubly valuable.

The new arrangement completely removes all sliding contacts from the galvanometer circuit and thus frees this important circuit from the thermal electromotive forces which are developed by the usual type of sliding contact. An elementary diagram of the apparatus is shown in fig. 6. The battery B

sends a current through the circuit B–P–D–R–A–B, this current being measured by the ammeter A. The contact P may be moved until the fall in potential along P–D, due to the battery current, is just equal to the voltage of the thermal-junction system TT. When this condition is fulfilled—as indicated by the absence of a galvanometer deflection—the voltage of the thermal-junction system may be computed directly from the constants of the apparatus. As before, however, the temperature difference between the junctions rather than their voltage is desired; and this may be obtained in the usual way by calibration.

The complete wiring diagram is shown in fig. 7. It will be noticed that, as in the older type of apparatus, the ammeter A is replaced by a standard cell N and galvanometer; also a variable resistance V is included in the main circuit for adjusting the current always to approximately the same value;[1] and the galvanometer is provided with a number of switches by means of which it may be connected to any one of a series of thermal-junction pairs, or to the standard cell circuit. The circuit has a great many features in common with that of the earlier apparatus previously described in detail,[2] and these need not be considered again at this point. Some differences, however, will be noted. The galvanometer sensitiveness is independent of the position of the contact P, since moving this contact in no way affects the resistance of the galvanometer circuit. The sensitiveness being constant, a resistance W has been inserted in the galvanometer circuit, and by this means the sensitiveness adjusted until the deflection reads directly in hundredths of a degree. No special provision is made for reversing B and N, as experience with the earlier apparatus showed this to be unnecessary. The new apparatus differs from the old, also, in that the thermometer must be detachable. Two heavy wires have therefore been run to two metal blocks in each calorimeter,

Fig. 6. Elementary wiring diagram of modified apparatus. Current from the battery B flows through PD, this being part of the slide wire CD, then through the resistance R and finally returns to the battery through the ammeter A. The thermal junction system TT is connected through the galvanometer G to the points C and D, this circuit being free from sliding contact.

and to these the thermometer can easily be attached. It will be noted in fig. 7 that each calorimeter is not provided with an entirely independent set of connections, but that the chair calorimeter and calorimeter No. 4 are connected in parallel, as are also calorimeters Nos. 3 and 5. This is allowable because other considerations prevent the calorimeters thus joined from ever being used at the same time.

_____

[1] It will be seen that the method as described is approximate only, and not exact, since the measuring current changes with each position of P. The error thus introduced may be made negligibly small for any case by making R sufficiently large as compared with CD. The resistance CD should be kept small from another standpoint as well, namely, that of sensitiveness. By the use of some kind of compensating resistance, equal to CD and arranged so as to be decreased as CD is increased, and vice-versa, the arrangement can be made exact.

[2] See pp. 14–22.

The apparatus is designed to measure temperatures to 0.02° C., and has a range of 8° C. The voltage of the cell B is 1.4 volts; that of N, 1.0197 volts.
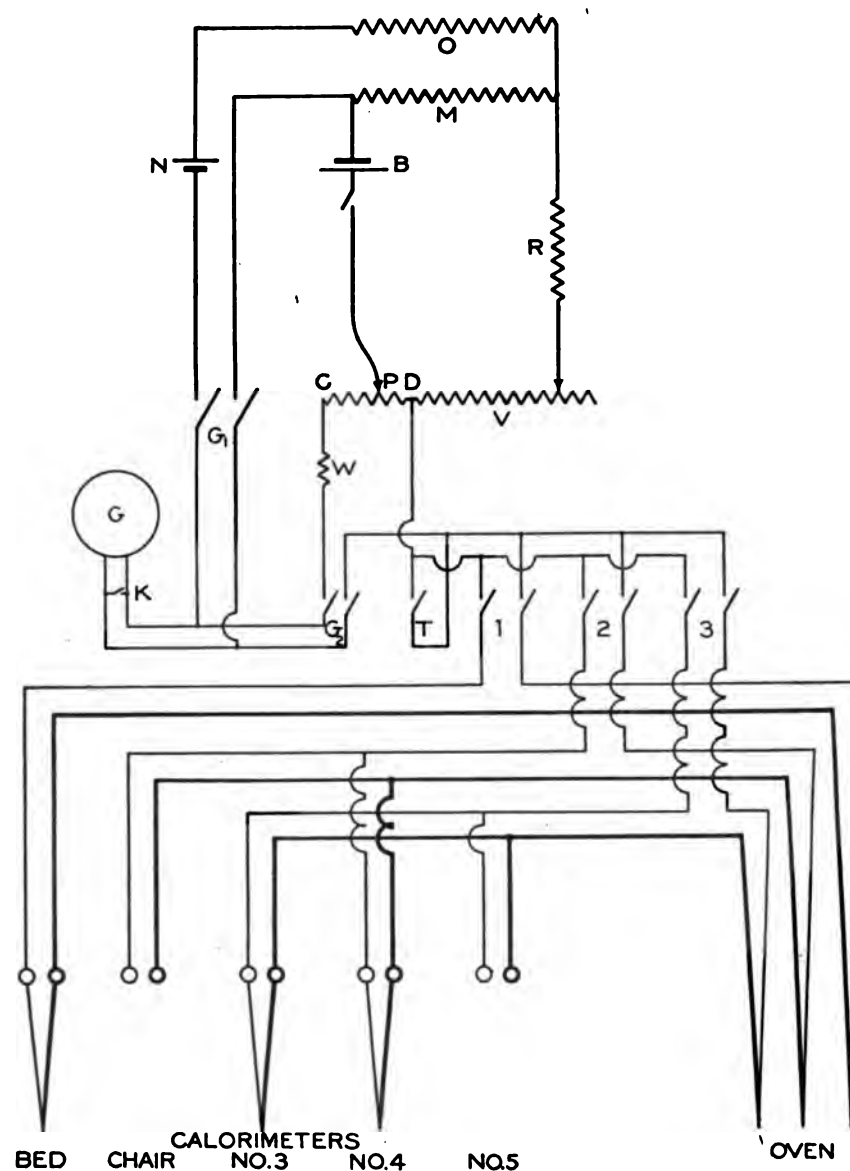
Fig. 7. Complete wiring diagram of modified apparatus. Current from the battery B flows through a portion (PD) of the slide wire CD, then through the resistances V and R, and returns to the battery through the resistance M. The points C and D are connected without sliding contact to the switching arrangement, of which G_1 connects the galvanometer G in circuit, T replaces the thermal junction system when testing, and 1, 2, and 3 are connected to the thermal junctions in the calorimeters and the constant-temperature oven. The constantan wires are indicated by the heavy lines; the calorimeter thermometers are detachable at the small circles. W is a resistance for adjusting the galvanometer sensitiveness. N is the standard cell, protected by the high resistance O, and connected to the circuit through the double contact key G_1. The switch K is for convenience in bringing the galvanometer to rest.

Copper-constantan couples are used, as previously. The slide wire C–D has a resistance of 0.372 ohm, and is divided into 400 divisions, each of which represents 0.02° C. temperature difference; M has a value of about 1200 ohms; and R, about 400 ohms. The maximum resistance of V is about 100 ohms; this should be variable in steps of about 1 ohm each. The value of W has not been measured, this resistance having been adjusted by trial. O, as before, is 10,000 ohms. For B a dry cell is used, from which a measuring current of about 0.00086 ampere is drawn; N is the Weston Standard cell used
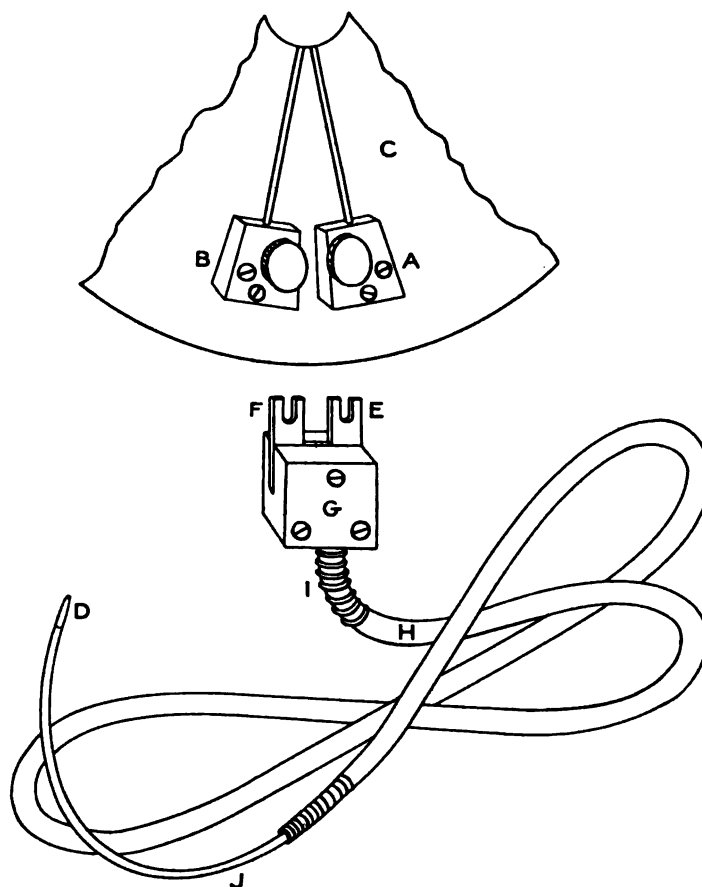
Fig. 8. Detachable thermometer for use inside the calorimeter, with connections. A and E are of constantan; B and F of copper.

previously. The potentiometer C–D consists of a 0.6 millimeter manganin wire, arranged in the form of a circle, the sliding contact P being operated by a knob at the center. The resistances M, R, V, and O are of manganin.

The constantan wire from the constant-temperature flask to the inside of the calorimeter is 2.05 millimeters in diameter, insulated with rubber and covered with a protecting braid. As will be seen in fig. 8, this wire is soldered

at the calorimeter to a small constantan block A, and in the same way the copper wire running to the calorimeter is soldered to a small copper block B. These blocks are mounted on a hard-rubber base C, and are provided with binding screws of constantan and copper, respectively, by means of which the thermal junction may be connected to the circuit without the intervention of any metal other than the two required for the thermometer itself.

The thermometer consists of two wires 1.6 meters long, 0.0455 millimeters in diameter, of constantan and copper respectively, well insulated, and soldered together at one end D. At the other end the wires are screwed to two flat terminals of constantan E and copper F, which are shaped to be received by the binding screws already mentioned. These flat terminals are mounted on a hard-rubber block G to which the wires are fastened in such a way as to make the joint absolutely rigid. The wires are covered by a 6.4 millimeter rubber tube H down to some 25 centimeters from the junction itself; this tube is protected by a spiral spring I at the point where it leaves the hard-rubber block G. This comparatively heavy tubing is continued by a smaller thin-walled rubber tube J for the remainder of the distance to the thermal junction; this thin tubing fits tightly around the wires and is closed at the end D by being tied tightly with silk.

It should be remarked that considerable trouble has been experienced by extraneous electromotive forces developed at the point where the constantan wire from the thermal junction is soldered to the flat constantan terminal E. This stray electromotive force has been found to be reduced practically to zero when the soldered connection is replaced by a clamp connection, made by fastening the wire under the head of a small constantan screw, without the use of solder. Apparently in this case the electromotive force is due not to difference in the constitution of the two pieces of metal, but rather to the unbalanced effect of the constantan-solder and solder-constantan couples. This leads to the conclusion that when it is necesary to solder two pieces of metal of identical constitution together, stray electromotive forces will be less likely to be developed if the two pieces have the same size and shape and are surrounded by as nearly as possible the same conditions of heat loss.

The operation of the apparatus is identical in procedure with the earlier form. The current is first balanced, after which the potentiometer balance is found, partly by setting, partly by deflection. Occasional observations are also required of the temperature in the oven and the stray electromotive force.

PART III.—DISCUSSION OF RESULTS.

While this investigation was primarily undertaken to study simultaneously the temperature in different parts of the body, many secondary points of considerable importance were naturally encountered in the process of the investigation.

THERMAL GRADIENT OF THE BODY.

The method of electrical measurement here outlined, owing to its extreme sensitiveness and delicacy, is admirably adapted for a study of the thermal gradient of the body. As has been previously shown, with an internal body-temperature of not far from 37° C. and a surface temperature of about 32° C. one would expect normally a thermal gradient. The exact significance of this gradient may be better understood after a consideration of certain points with regard to the physical structure of the body. If the highest heat production were at the exact center of the body and there was a definite thermal gradient from the center to the skin, it is obvious that the measurement of body-temperature, particularly the average body-temperature, would present almost insuperable difficulties. One could not select a point half-way between the surface of the skin and the center of the body and assume that the temperature at this point would represent the average body-temperature, since there would be no way of obtaining a record of this temperature. On the other hand, if the thermal gradient rose sharply for the first few centimeters beneath the surface of the skin and soon reached a point beyond which the body temperature was not materially increased, the problem would be much less complicated. If, as is frequently the case, we desire to note the total amount of heat actually latent in the body at a given time, we must know the body-temperature as nearly as possible. Consequently a study of the thermal gradient was first made.

METHOD OF STUDYING THE THERMAL GRADIENT.

In studying the thermal gradient, the rectum was used with men, and the rectum and the vagina with women, both being deep cavities into which the thermal junctions could be inserted for a considerable distance. It is obvious that at the entrance of either of these cavities the temperature will be low, $i. e.$, that of the environment, but as the thermal junction is inserted deeper into the cavity, the temperature more nearly approximates that of the interior portion of the body. The important point to note, then, is the depth of insertion required to obtain the maximum temperature. For this purpose, two thermal junctions were inclosed in a single tube, and bound together in such a way that one was exactly 3.5 centimeters from the other. This tube was then inserted in the cavity to be studied, so that the deeper junction was approximately 10 centimeters within the cavity and the other accordingly 6.5 centimeters. Readings were taken until constancy had been obtained; then both thermometers were withdrawn to a new location in the cavity, and the measurement repeated. By this means the whole region was studied, the two ther-

mometers allowing simultaneous observations, each serving as a check upon the other. With women, observations could be made simultaneously in the rectum and the vagina.

EXPERIMENTAL RESULTS.

The results are expressed in the form of curves (see figs. 9, 10, 11, 12, and 13), in which the depths of insertion are expressed by horizontal distances, the corresponding temperatures being represented vertically. The records for rectal observations are marked R_D and R_s for the deep and shallow temperatures respectively; in a similar manner the curves for the deep and shallow vagina are designated by V_D and V_s. In some instances, when only a single thermometer was used in either cavity, the subscript is naturally omitted.
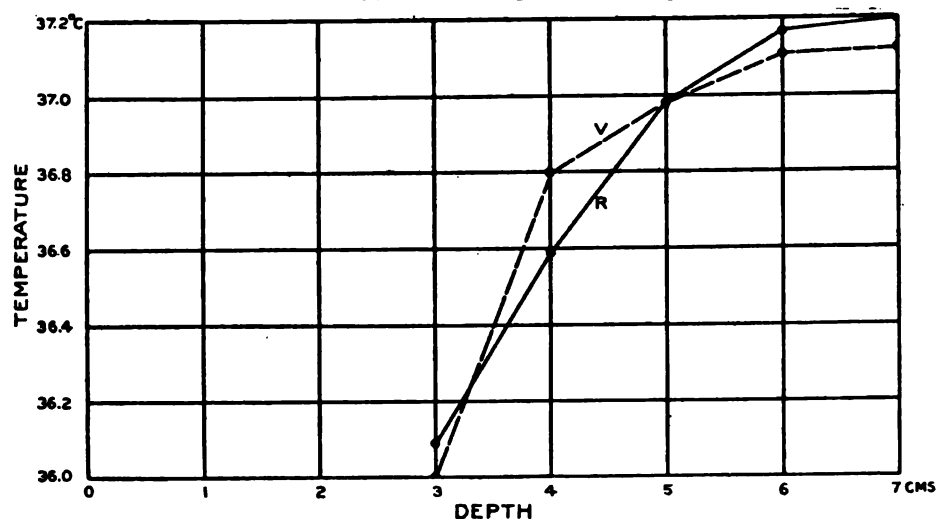
Fig. 9. Observations on thermal gradient, with Mrs. B—1.

In the experiment represented by fig. 9, observations were made on a woman (Mrs. B—1) with one thermometer in the rectum and a second in the vagina, the double thermometer not being used in either case. The actual temperature observations are given in table 5.

The results show that at a depth of 3 centimeters in either cavity the temperature was over a degree lower than at a depth of 7 centimeters. The rise was rather regular and gradual up to 5 centimeters; beyond that point the rise was much slower and between 6 and 7 centimeters it nearly ceased, in-

TABLE 5.—*Thermal gradient observations.*

Rectal thermometer.		Vaginal thermometer.	
Insertion.	Temperature.	Insertion.	Temperature.
cm.	*°C.*	*cm.*	*°C.*
7	37.20	7	37.12
6	37.17	6	37.11
5	36.98	5	36.98
4	36.59	4	36.80
3	36.09	3	36.00

dicating that in this case and under the conditions of the experiment, the maximum body-temperature was reached when the thermometer was inserted 6 or 7 centimeters in the vagina or the rectum.

37.0°C

36.8

36.6

36.4

36.2

36.0

35.8

35.6

35.4

35.2

35.0

34.8

34.6

34.4

34.2

34.0

TEMPERATURE

R_D

R_S

0 1 2 3 4 5 6 7 8 9 10 11 12 CMS.

DEPTH
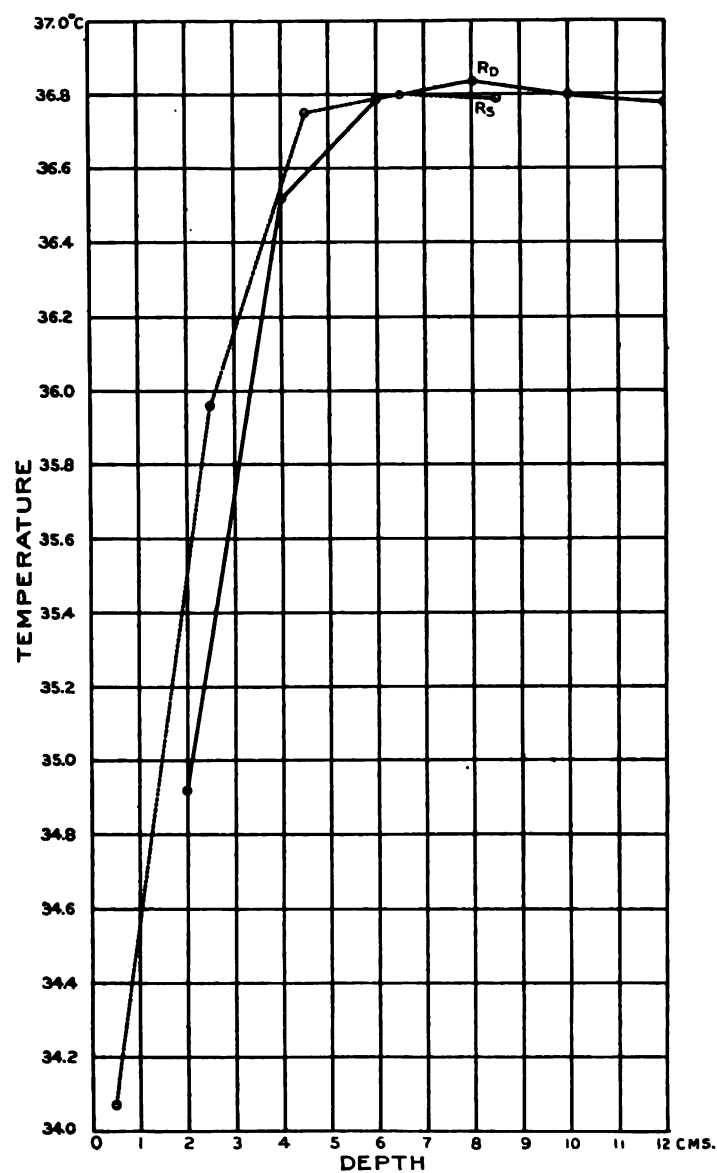
Fig. 10. Observations on thermal gradient, with C. H. H.

In the experiment represented by fig. 10, a double thermometer was used in the rectum, one of the laboratory assistants (C. H. H.) serving as a subject. It is interesting to note from the curves that between the depths of 0.5 centimeters and 6 centimeters, there is a difference in temperature amounting to 2.72° C. The curves rise very rapidly until the depth of 4 centimeters is reached, continuing to rise much more slowly for the next 2 centimeters. Apparently with this subject the temperature reached its highest point at a

depth of about 6 centimeters, and from 6 to 12 centimeters there was no material variation.
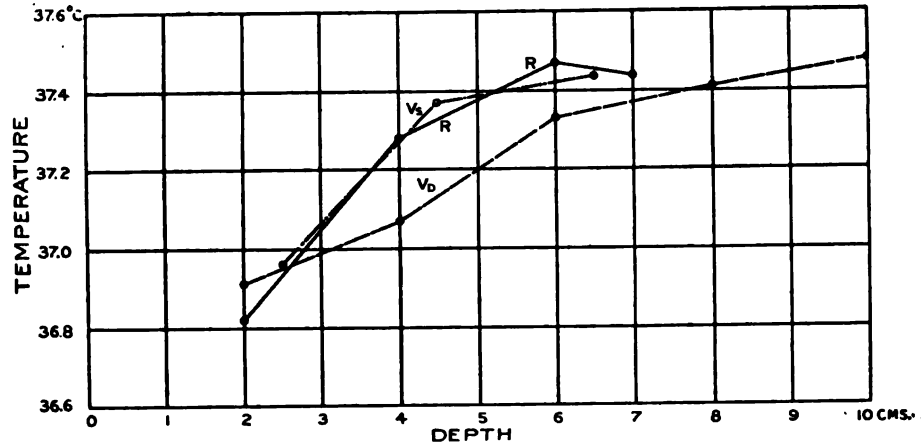
Fig. 11. Observations on thermal gradient, with Mrs. B—1.

The experimental results shown in fig. 11 were obtained with the woman subject previously mentioned, a double thermometer being used in the vagina and a single thermometer in the rectum. The curves show in a general way the characteristics of the curves in the preceding tests, although the gradient is not so sharply indicated.
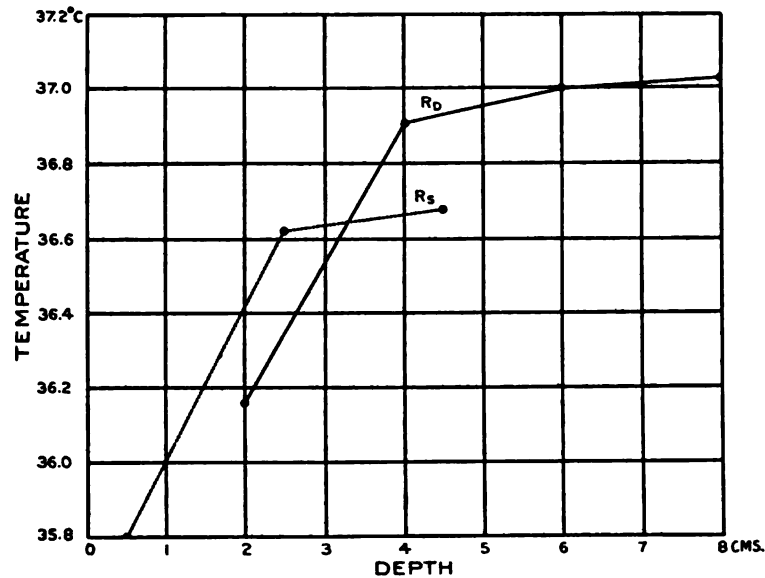
Fig. 12. Observations on thermal gradient, with J. J. C.

A thermal-gradient experiment was made with another laboratory assistant (J. J. C.) in which a double thermometer was used in the rectum, the results being shown in fig. 12. With this subject the temperature at a depth of 0.5

centimeters was 35.80° C., and at 8 centimeters 37.03° C. No material differences were noted between 6 and 8 centimeters. As usual the gradient rose very sharply up to a depth of 6 centimeters, after which the temperature remained practically constant.

The records for a third experiment with the woman subject are given in fig. 13; in this experiment a single thermometer was used in the vagina and a double thermometer in the rectum. The temperature rose very rapidly until about 5 centimeters was reached; afterwards it remained essentially constant for the remaining distance between 5 and 10 centimeters, beyond which point it was not studied. The temperature at 2 centimeters was about 36.8° C. and at 10 centimeters 37.3° C., showing a difference of approximately 0.5° C.
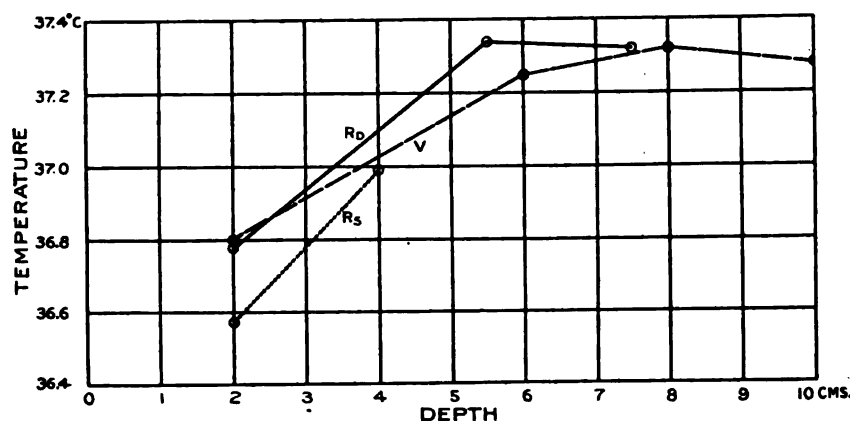
Fig. 13. Observations on thermal gradient, with Mrs. B—1.

GENERAL CONCLUSIONS WITH REGARD TO THE THERMAL GRADIENT.

It is apparent, therefore, that the thermal gradient between the temperature at the surface of the body and at a depth of about 5 centimeters is quite noticeable; evidently beyond 5 centimeters the body-temperature is essentially at its maximum. It has been neither disproved nor shown by this study, of course, that the temperature may not be actually higher in the liver or in some other active organs of the body; indeed, it is to be expected that where there is special metabolic activity, as in the liver and other glands, there might be a somewhat higher temperature. On the other hand, Rancken and Tigerstedt,[1] who found that ordinarily the temperature in the stomach was about 0.1° C. higher than that in the rectum, were unable to note any rise in temperature during the first hour of active digestion, except such as was due to the heat of the food. However, in finding the average temperature of the human body, it appears safe to say that the temperature rises to its highest point at a depth of 6 to 7 centimeters.

[1]Rancken and Tigerstedt, Biochem. Zeitsch., 1908, 11, p. 36.

From the very sharp gradient, it may be easily inferred that the surface temperatures of the body, or those slightly below the surface, are liable to the greatest errors in determination, and consequently, as ordinarily measured, they can have but little physiological significance.

SELECTION OF LOCALITIES FOR SIMULTANEOUS MEASUREMENT OF FLUCTUATIONS IN BODY-TEMPERATURE.

NATURAL CAVITIES.

The rectum and the vagina used alone are not especially suitable for studying the constancy or the lack of constancy of temperature fluctuations in different parts of the body, since these two cavities are side by side. Unfortunately no other cavity presents such ideal conditions for the study of fluctuations in body-temperature as do these, the only other openings which could be used being the mouth and the œsophagus. While it has long been the custom of physicians and physiologists to take temperatures in the mouth, certain grave objections have been raised to the use of this locality, and it is obvious that a more careful study of buccal temperature should be made before relying upon this cavity for exact temperature measurements. Accordingly, a considerable amount of experimenting was done in connection with this research to test the reliability of temperatures taken in the mouth.

TEMPERATURE MEASUREMENTS IN THE MOUTH.

A variety of methods were used for taking mouth temperatures, but even when extreme care was observed, the results were unsatisfactory. The experiment was tried, for instance, of inserting a thermal junction beneath the tongue and recording the temperature until it became constant; the thermal junction was then withdrawn and immediately replaced by a carefully calibrated clinical thermometer[1] which was allowed to remain in position for 5 minutes. The temperatures indicated by the two measurements were not identical, the thermal junction giving results 0.2° to 0.4° F. lower. Again, the mercurial thermometer and the thermal junction were fastened together and inserted beneath the tongue for a period of possibly 20 minutes, the thermal junction being read at regular intervals until a maximum was reached, this requiring some 15 minutes. When the maximal reading was compared with the clinical thermometer reading it was found to be 0.1° to 0.3° F. lower than the latter.

This continual disagreement led to a doubt as to the wisdom of using this locality for taking temperature records, and of the clinical thermometer as a standard. As a further test, the experiment was then tried of tying two clinical thermometers together, inserting them in the mouth, and removing them at the end of 5 minutes to take the records. After the thermometers had been shaken down, they were replaced in the mouth and further 5-minute

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[1] Inasmuch as the Fahrenheit degree is employed in graduating practically all of the mercurial clinical thermometers used in this country, this unit is made the basis of the discussion of buccal temperatures, although in all other sections of the report the centigrade scale is regularly used.

records taken. For approximately 10 minutes the readings of the two thermometers disagreed; afterwards they were identical. This led to the belief that unequal conditions of heat loss caused the discrepancies observed in the earlier readings. To equalize this heat loss, warm water was held in the mouth and simultaneous records taken with the thermal junction and the clinical thermometer, the water acting in a way as a protection from outside temperature influences. The results showed the thermal junction in one instance to have the same maximal temperature as the clinical thermometer, but usually it was 0.2° to 0.3° F. lower. Then the thermal junction was embedded in paraffin, and its records compared with those of the clinical thermometer. The results showed that even under these conditions the thermal junction readings ranged from 0.1° higher to 0.3° F. lower than those of the clinical thermometer.
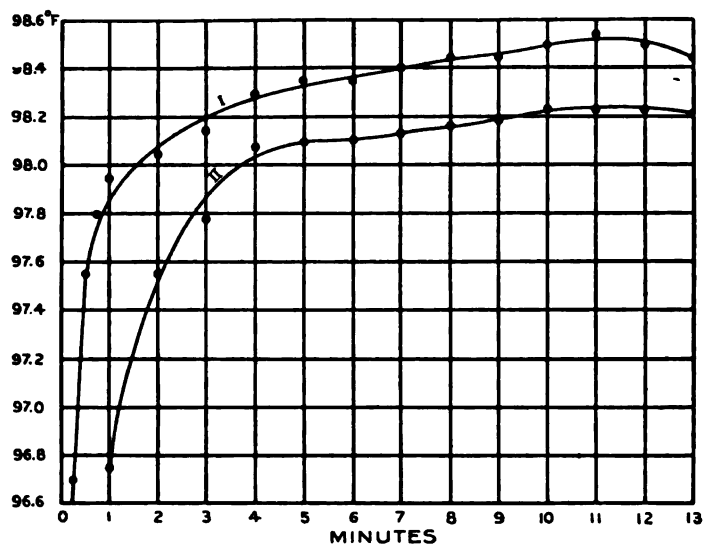
F. 14. Observations showing the rise of temperature in the mouth.
(I) clinical thermometer, (II) thermal-junction thermometer.

Finally the design of the thermal junction was changed. In all of the previous experimenting with the mouth temperature, a junction of either type A or C (fig. 3) was used.[1] The new junction was built with a heavy, pear-shaped, copper element, the bulb of which was about 1 centimeter in diameter. The constantan element, a small wire, was soldered to the copper at about the center of the bulb, by means of a small hole drilled through to this point. This junction was then compared with the clinical thermometer, as in the previous experiments. The results obtained from six comparisons show that the thermal junction and clinical thermometer agreed in three cases, the thermal junction was 0.1° F. higher than the clinical thermometer in two cases, and 0.2° F. higher in the remaining case.

[1]See p. 18.

Two curves are reproduced in fig. 14, showing records obtained in the mouth with a clinical thermometer and with a thermal-junction thermometer. In these curves the intervals of time during which the thermometer was held in the mouth are expressed by horizontal distances, the corresponding temperatures being represented vertically.

Curve I may be of interest in showing that a clinical thermometer inserted beneath the tongue does not attain its maximal temperature for a considerable time. The curve was obtained in the following way: A subject carefully trained to the use of a clinical thermometer, after preparing for the experiment by keeping his mouth closed for perhaps 10 minutes, seated himself and placed a clinical thermometer beneath the tongue, allowing it to remain for 15 seconds. He then removed the thermometer, read it, quietly shook it down, and replaced it, this time for 30 seconds. This procedure was repeated, the thermometer being kept in place during constantly increasing periods of time up to 13 minutes. Even after the thermometer had been inserted 7 minutes, a further rise of over 0.1° F. was noted; this, it would seem, must have been caused by the slowness of the cavity in warming up, as the true body-temperature must have been slowly falling on account of the quietness of the subject.

Curve II was obtained shortly afterwards with the thermal junction; in this case, however, the procedure was greatly simplified. The thermometer was inserted at a definite instant and its temperature taken each minute by means of the usual measuring apparatus. The curve is similar in shape to that obtained with the clinical thermometer; the maximal temperature indicated is, however, somewhat lower.

Having obtained such inconstant results in the mouth with these two types of thermometers, an attempt was made to find out if better comparisons could not be obtained in the rectum. The experiment was accordingly tried of inserting the thermal junction about 7 centimeters into the rectum, taking readings for perhaps 15 minutes until constancy was assured, then removing the thermometer and replacing it by a clinical thermometer inserted to the same depth. The results given by the thermal junction varied from 0.1° F. lower to 0.2° F. higher than the clinical thermometer.

When the thermal junction and the clinical thermometer were fastened together in a single rubber tube and inserted in the rectum, the maximal reading of the thermal junction in one case was identical with that of the clinical thermometer, while in another instance it was 0.2° F. lower than the clinical thermometer. This pointed to an error in the thermal-junction reading, but a further test was made which showed that the reading of the clinical thermometer was by no means an indisputable standard. In this test, two carefully calibrated clinical thermometers were inserted in a rubber tube and placed in the rectum. After 10 minutes they were withdrawn, carefully removed from the tube, and read. The readings were not identical, but disagreed by 0.1° to 0.2° F.

In order to make sure that the presence of the rubber tubing did not vitiate the results, a thermal junction and a clinical thermometer were inclosed in

rubber tubing exactly as for an experiment. They were then immersed in a bath of warm water and readings were taken continuously of the thermal junction temperature; at the end of 10 minutes, they were withdrawn from the water, the tubing removed, and the clinical thermometer read. In one test, at a temperature of 98° F., the reading of the clinical thermometer agreed exactly with the record obtained with the thermal junction; in a second test, at a temperature of about 99.4° F., the records disagreed by 0.4° F. Shortly afterwards the clinical thermometer used was broken, so that this result could not be verified.

Although no definite conclusion was reached, these comparison experiments left in the minds of the experimenters grave doubts as to the feasibility of using the mouth in temperature observations, and also an indefinite distrust of the clinical thermometer for accurate work. It should be stated that a type of mercurial thermometer was used that probably represented as good an instrument as is ordinarily available, selection being made from a number of thermometers that had been simultaneously calibrated. It is evident that the rise of mercury in the thread in a series of impulses may easily lead to errors as great as 0.2° F., and hence whatever value the mercury self-registering thermometer has to the clinician, it can have little, if any, value when accurate body-temperature measurements are desired.

ARTIFICIAL CAVITIES.

In the effort to find favorable places for making temperature observations, certain artificial cavities, such as the closed axilla or groin, or between the closed hands, were carefully studied. These so-called cavities are really more or less exposed portions of the skin, the configuration of which has been changed so as to form a closed pocket. On account of the large amount of subcutaneous fat, greater possibilities for finding such cavities are afforded with women than with men; accordingly, in experiments with a woman attempts were made to study the temperature fluctuations by means of a thermometer placed between the arm and the breast, between the two breasts, and in different parts of the body more or less inclosed by flesh.

The one great difficulty with all of these so-called artificial cavities is that they require considerable time to warm them to the maximum temperature. The temperature of the exposed skin before the cavity is made may be as low as 32° C., while that in the inclosed cavity, equilibrium having once been established, may be 36° or 37° C. At the beginning of a test, therefore, the cavity will have a temperature not far from 32° C., and will gradually become warmed to 36° C. or thereabouts, before it can be used for comparison with natural cavities, such as the rectum and the vagina. The warming-up period usually occupies 20 or 30 minutes for the axilla, the length of the period depending principally on the closure obtained. For the cavities made by the groin and by the hands, the preliminary warming period is even longer, since these cavities are formed from places ordinarily less inclosed than the axilla. To avoid this loss of time, a hot-water bottle, previously filled with water at

a temperature 2° or 3° C. higher than that of the body, was placed in the inclosed portion for 5 minutes before inserting the thermometer. By this means the cavity was preheated to approximately normal temperature, and came to its final value in about half of the time previously required.

SIMULTANEOUS OBSERVATIONS OF BODY-TEMPERATURE IN DIFFERENT LOCALITIES.

From the previous discussion of the thermal gradient it is obvious that it would be practically impossible to determine the average temperature of the human body, although as a gradient effect is most marked in the last peripheral 4 centimeters of body material, a large portion of the body would have a temperature not far from that of the rectum. Fortunately, for purposes of calorimetry, what is chiefly desired is the fluctuations in temperature from hour to hour or from day to day. One must be sure that the fluctuations in temperature throughout the whole body are of equal value, since otherwise no accurate estimate can be made of the total heat gained or lost due to a rise or fall in temperature.

The temperature of the body rarely remains constant, even for so short a time as 10 minutes; this was shown by a series of observations[1] made every 4 minutes for several days in which practically no two consecutive readings were exactly alike. The normal temperature rhythm, with a maximum between 4 and 5 o'clock in the afternoon and a minimum between 2 and 5 o'clock in the morning, is considerably accentuated by a number of extraneous factors, but even with the subject lying in bed without food, or with a small amount of food, the range in temperature in 24 hours may be as high with a normal subject as 1.3° C. (2.3° F.).

In the collected results of body-temperature measurements obtained in a large number of experiments with the respiration calorimeter at Wesleyan University, Benedict and Carpenter[2] report that the average body-temperature in experiments with food was 36.82° C. (98.3° F.), the minimum being 35.67° C., and the maximum, 38.23° C. The average range for all of the experiments was 0.96° C., the minimum range, 0.44° C., and the maximum, 1.64° C. In a series of experiments with 11 subjects in which food was not taken, covering in all 31 days of 24 hours each, the average temperature of the subjects was 36.67° C. (98° F.). The minimum temperature observed was 35.53° C., and the maximum, 37.74° C. The average range in temperature was 0.77° C., the minimum range being 0.38° C., and the maximum, 1.36° C. (2.45° F.).

The large number of observations made on body-temperature by electrical methods in the last few years have shown that there are fluctuations aside from the normal rhythm—fluctuations that can be produced artificially; for example, changing from a lying to a sitting position will cause a slight rise in temperature, as will also the taking of hot drinks or hot food. Eating a meal may cause a rise of as much as 0.15° C. in 20 minutes, and severe muscular

[1]Benedict and Snell, Archiv f. d. ges. Physiol., 1902, 90, p. 33.
[2]Benedict and Carpenter, Publication No. 126, Carnegie Institution of Washington, 1910, p. 121.

work as much as 0.50° C. in 30 minutes. In fact, any increase in body activity tends to increase the temperature. On the other hand, muscular relaxation and sleep, as well as cold water and cold food, will cause a fall in temperature. Consequently, in certain of our experiments the effort was made by various means to produce artificially these fluctuations in temperature in order to enable us to secure better conditions for measurements of temperature fluctuations in different parts of the body.

The 24 experiments in this study of body-temperature were all made with healthy people, including five men and one woman; the data regarding the age, height, and weight of these subjects may be found in table 6. With but few interruptions, the experiments continued daily from the beginning of January until the middle of March, 1911. The experimental conditions remained essentially the same throughout the series, save that in all experiments prior to January 27, 1911, the water in the Dewar flask inside of the constant-tempera-ture oven was not stirred by compressed air. While this change in the apparatus tended to insure a constancy of temperature that added somewhat to the accuracy of the subsequent results, nevertheless the experiments were usually of short duration, and hence were not subject to wide errors due to imperfect stirring.

Previous to an experiment, the ther-mometers were adjusted and the subject immediately lay down on a comfortable couch or occasionally sat in a chair, chang-ing the position from time to time to avoid

TABLE 6.—*Age, height, and weight of subjects.*

Subject.	Age.	Height.	Weight without clothing.
	years.	cm.	kilo.
Mrs. B—l..	43	164	56
F. G. B....	40	183	83
J. J. C....	27	175	65
C. H. H...	18	169	55
V. G......	17	162	55
F. A. R....	34	163	74

extreme discomfort. In each experiment one main question was usually studied, and incidentally numerous minor points. In giving the results, therefore, it seems best to present the curves for each experiment by itself, with the conclusions drawn therefrom, and finally to summarize the results and give the conclusions drawn from the experiments as a whole. In these curves, as usual, the time is expressed by distance measured horizontally and temper-ature is represented vertically. The records for the various localities are designated as follows: Deep rectum, R_D; shallow rectum, R_s; deep vagina, V_D; shallow vagina, V_s; right axilla, A_x; left axilla, A_L; mouth, M; groin, G; upper leg, L; hand, H_c and H_r; and various surface points, S.

EXPERIMENTAL RESULTS.

Experiment of January 6, 1911, *with C. H. H.*—A thermometer was placed in each axilla, and two thermometers in the rectum, one of the latter being inserted 10.4 centimeters, and the other 6 centimeters. The experiment began shortly after the subject reached the laboratory in the morning, and it will be noticed that in consequence there was an initial fall in temperature of both the rectal thermometers. This is usual after muscular exercise, even so

limited an amount of exercise as would be incidental to coming to the laboratory. The length of time required to raise the temperature in the axilla to constancy was from 20 to 30 minutes; when constancy had been assured, the axillas were opened and cooled for a short time, and the thermometers again inserted.

The two axillas had about the same temperature curve, and in a general way the fluctuations followed those in the rectum; the records of the axilla thermometers were, however, lower than those of either the shallow or the deep rectal thermometer.

The results of the measurements are shown in fig. 15, in which the curves are marked as previously indicated.
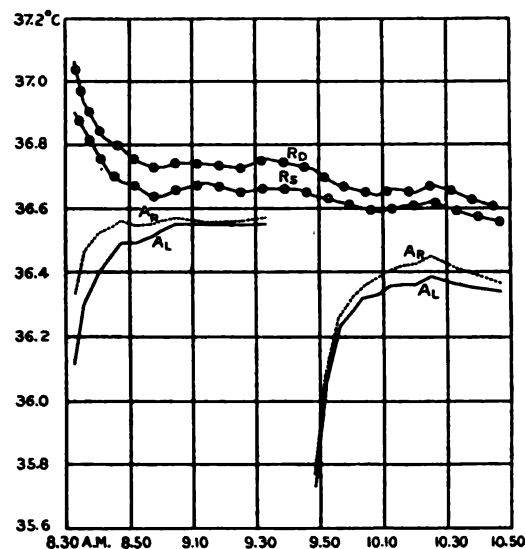
Fig. 15. Temperature curves for experiment of January 6, 1911, with C. H. H.

Experiment of January 6, 1911, with Mrs. B—l.—This experiment was made primarily to test the feasibility of obtaining the body-temperature of women. The subject came to the laboratory after the noon meal and immediately lay down upon the couch. A single thermometer was inserted in the rectum to a depth of 7 centimeters and a second thermometer in the vagina. A thermometer was also placed in the right axilla, the subject lying on the same side to keep the cavity closed. No special bandages were used. In addition, a fourth thermometer was placed under the breast, with the breast folded over it as much as possible and kept in place by a bandage. At 4ʰ 23ᵐ p. m., the thermometer was removed from under the breast and placed in the groin; the axilla was also opened at this time, and the thermometer replaced in the cavity at 4ʰ 34ᵐ p. m. The curves for the rectum and the vagina had agreed remarkably well until this time, but during the change the vaginal thermometer was accidentally moved out of position and the temperature record changed to a level a little over 0.5° C. below the original. After the vaginal thermometer

had slipped out, it was unquestionably more or less covered by the labia and the fleshy portion of the leg, so that the temperature was not extremely low. The subject lay in a somewhat curled-up position after the placing of the thermometer in the groin, which helped to keep the record of the vaginal thermometer high in spite of the fact that it was not deeply inserted.

An unusually long time was required for the thermometers in the artificial cavities to reach constancy, this being unquestionably due to the imperfect closing of the cavities. The curves for these localities follow each other quite closely, but illustrate admirably the difficulty of securing proper temperature records without special precautions for perfect closure.
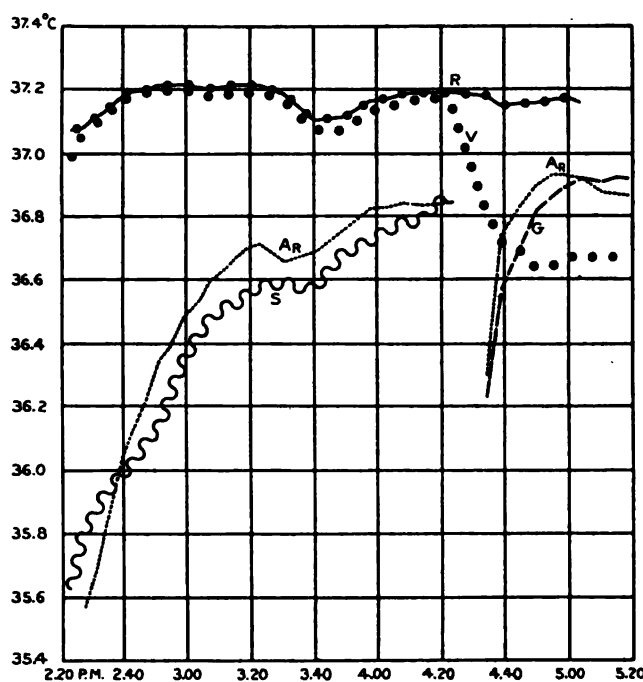
Fig. 16. Temperature curves for experiment of January 6, 1911, with Mrs. B—l.

The results of the temperature measurements are given in fig. 16. The curves for the rectal and axilla thermometers are marked in the usual way, while the curve for the vagina is designated as V, that for the thermometer placed under the breast as S, and for the thermometer in the groin as G.

Experiment of January 7, 1911, *with J. J. C.*—Both the deep and the shallow thermometers were used in the rectum, inserted to a depth of 10 centimeters and 5 centimeters respectively. Temperature records were also taken simultaneously in both axillas, the arms being folded across the chest and held in place by cloth bandages so as to insure perfect closure. The subject sat in a chair during the experiment and was very sleepy. At 12^h 09^m p. m., both axilla thermometers were removed so as to give more freedom of movement. Between 12^h 16^m p. m. and 12^h 36^m p. m. the subject ate a dinner consisting

of steak, rolls, and coffee.   At 12ʰ 57ᵐ p. m. he changed to a more comfortable
lounging chair and the axilla thermometers were replaced.   At 1ʰ 35ᵐ p. m.
he put his feet up on another chair.

The occasional fluctuations noted in the curve for the shallow rectal ther-
mometer were probably due to the fact that the thermometer was not inserted
to a sufficient depth, as the observer noted that the temperature fluctuated
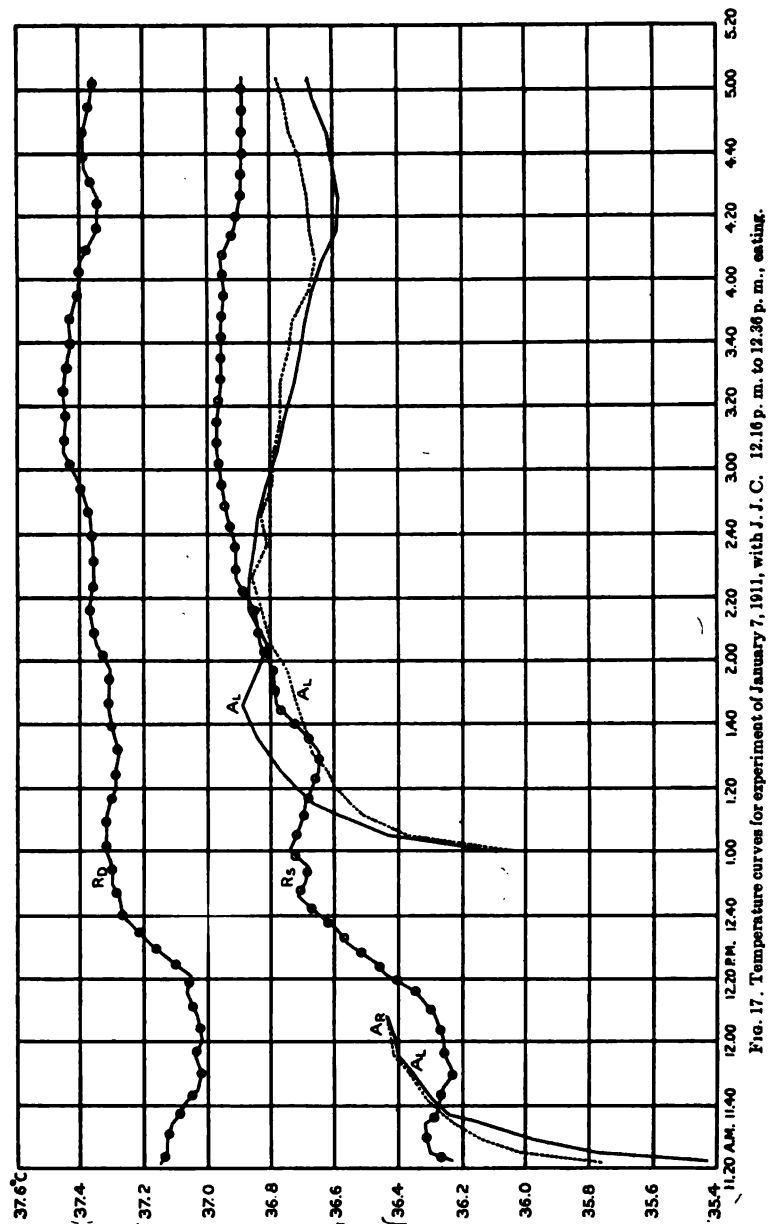
FIG. 17. Temperature curves for experiment of January 7, 1911, with J. J. C.   12.16 p. m. to 12.36 p. m., eating.

whenever the subject moved his legs. Of particular interest, however, is the fact that while the curve for the shallow rectal thermometer is much lower than that for the deeper thermometer, the two curves follow each other very closely, thus indicating simultaneously the temperature gradient previously discussed, and also a constancy in the curve of body-temperature at different parts of the body. The temperature curves for the axillas show, first, the long time required to warm the axilla to constancy, and second, the fact that unless special precautions are taken to hold the thermometers in place and fully covered with flesh, the results will have but little value. There is a marked lack of uniformity between the temperature curves for the axillas and that for the rectal thermometer. This can be explained only by the fact that the subject was very sleepy and proper precautions were not taken to
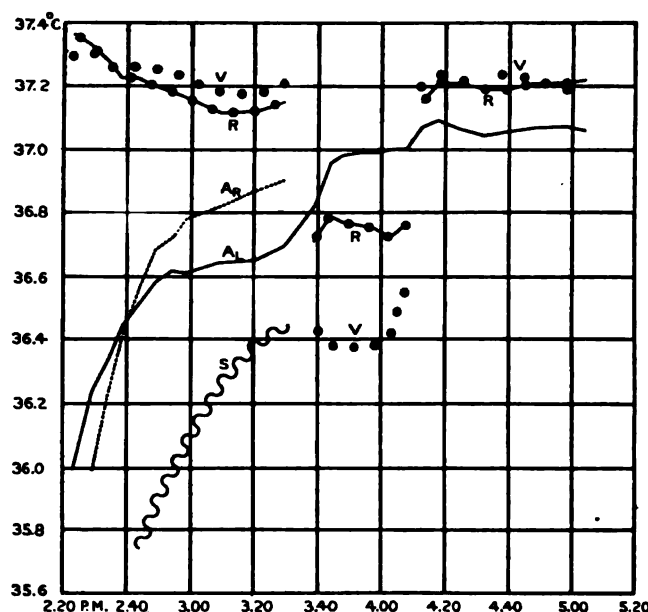
F. 1. 13.   Temperature curves for experiment of January 9, 1911, with Mrs. B—1.

insure a thorough closure of both axillas, although it is a significant fact that both the axilla temperature curves show a tendency to fall off at about the same degree of rapidity.

The results of the temperature measurements are given in fig. 17, the curves being designated in the usual manner.

Experiment of January 9, 1911, *with Mrs. B—1.*—A single thermometer was used in the rectum and another in the vagina, each being inserted to a depth of 7 centimeters. A thermometer was also used in each of the axillas and one between the breasts, which were drawn together and folded over the thermometer by means of a cloth belt. The thermometers in the artificial cavities required a long time to reach constancy, doubtless on account of the imperfect closure of the cavities. At 3^h 30^m p. m. both the thermometer in the right

axilla and the skin thermometer were removed; also, the rectal thermometer and the vaginal thermometer were each supposedly withdrawn 2 centimeters. At this time, however, the vaginal thermometer slipped out, causing a discrepancy in the records. At 4^h 09^m p. m. both the rectal thermometer and the vaginal thermometer were returned to their original positions, without disturbing the left axilla, and from this time on the curves agree very satisfactorily.

The results of the temperature measurements are given in fig. 18, the curves being marked as usual.

Experiment of January 11, 1911, *with J. J. C.*—This experiment was divided into three parts in order to study the rectal gradient, the effect of warming the axilla previous to inserting the thermometer also being studied. Two thermometers were used in the rectum, and one in each axilla. In the first part of the experiment, the deep thermometer was inserted in the rectum to the depth of 7 centimeters, and the shallow thermometer to the depth of 4 centimeters; in the second part, the insertions were 5.5 centimeters and 2.5 centimeters respectively; and in the last part, 3.75 centimeters and 0.75 centimeter.
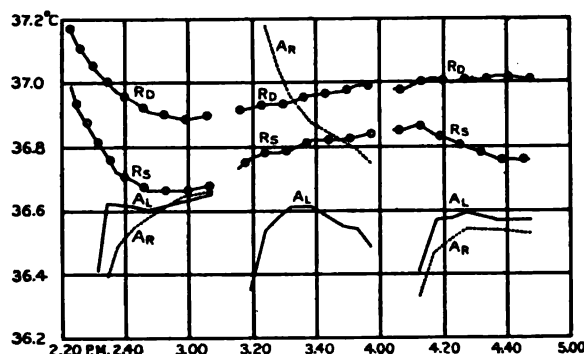
Fig. 19. Temperature curves for experiment of January 11, 1911, with J. J. C.

Previous to the first part of the experiment, a hot-water bottle, at a temperature of 40° C., was placed in the left axilla for 5 minutes, the thermometer being inserted in the right axilla, as usual without preheating. The effect of this preheating is shown by the fact that the curve for the left axilla rose more abruptly than that for the right. In the second part of the experiment, the conditions were reversed, a hot-water bottle with a temperature of 45° C. being used in the right axilla, but none in the left. Without doubt the temperature of the water used was too high, as the curve for the right axilla did not fall to the temperature level of the body for some time. In the third part of the experiment, the conditions of the first part were duplicated, the hot-water bottle at a temperature of 40°C. being placed in the left axilla, and the thermometer inserted in the right axilla without preheating the cavity. The same tendency to an abrupt rise in the curve for the left axilla was again noted, although it was not so pronounced as in the first part of the experiment. The curves for the rectal thermometers show the usual fall in temperature at the beginning of the experiment. It should be noted that the curves for the deep

and shallow rectal temperatures, by being roughly parallel but not coincident, indicate clearly the thermal gradient already discussed in considerable detail.[1] In view of this fact and that previous experiments indicate a similar gradient, a fall in temperature would be expected to follow the withdrawal of the thermometers to a less depth. This fall in temperature is not, however, shown. The discrepancy can be explained only by the fact that as the thermometers were adjusted by the subject, which involved considerable movement on his part, the statement regarding the depths of insertion is doubtless inaccurate.

The measurements of the body-temperature in the different localities are given in fig. 19, the curves being designated as usual.

Experiment of January 12, 1911, *with C. H. H.*—The deep and shallow rectal thermometers were used, also a thermometer in each axilla, the axillary thermometers being held in place by bandages. This experiment, like the preceding, was divided into three parts so that a study could be made of the rectal gradient and of the effect of preheating the axilla. In the first part of the experiment, the depth of insertion of the shallow thermometer was 6.5 centimeters, and of the deeper thermometer, 9.5 centimeters; in the second part, they were inserted 4 and 7 centimeters, respectively; and in the third part, 0.75 centimeter and 3.75 centimeters, respectively. A ho-twater bottle, at a temperature of 40° C., was placed in the left axilla 5 minutes before the experiment commenced, the right axilla not being preheated. In the second part of the experiment, the left axilla was again preheated by means of a hot-water bottle at the same temperature as before, while in the last part the hot-water bottle, at a temperature of 42.5° C., was used in the right axilla.

During the experiment, the subject apparently slept at times, but usually was lying awake and quiet. In the first part of the experiment, the left axilla had a temperature somewhat above that of the right, although the records for the two thermometers remained parallel after constancy had been obtained.
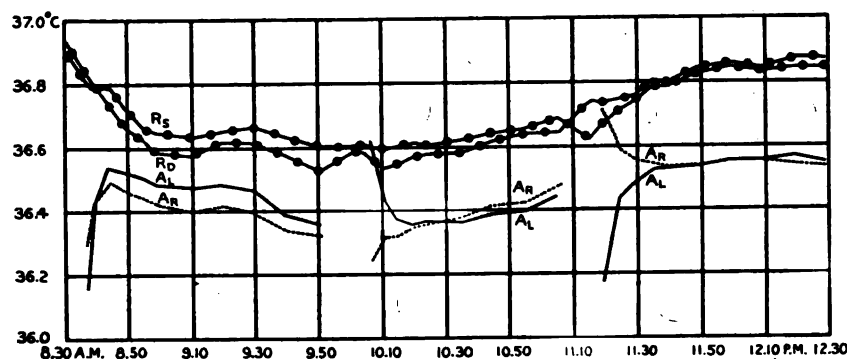
Fig. 20. Temperature curves for experiment of January 12, 1911, with C. H. H.

At the beginning of the second part, the temperature curve for the left axilla was above normal, but fell rapidly until the two axillary curves became essentially the same. In the third part of the experiment, the preheating of the

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[1]See p. 35.

right axilla raised the temperature above normal and consequently this curve shows an initial fall, while the curve for the left axilla rose as usual, becoming constant in approximately 20 minutes.

It is noted that here, as in the preceding experiment, the rectal temperature curves are apparently unaffected by a change in the depth of insertion. The explanation is probably the same as before, namely, that the depth of insertion was changed by the subject himself, and therefore the depths as stated may be very seriously questioned. The fluctuations in both the rectal curves follow each other with considerable regularity, the curves being in general parallel.

The measurements of the body-temperature are given in fig. 20, the designations of the curves being as usual.

Experiment of January 12, 1911, *with F. A. R.*—In this experiment a single thermometer was used in the rectum at a depth of 10.5 centimeters; also, two thermometers were placed between the hands, one in the center of the palms, the other near the base of the second finger. To provide for the closure for the two latter thermometers, the hands were firmly clasped and tied together with bandages. The curves for the hands show at first the slowness of the cavity in approaching its final temperature; then, beginning about $2^h 30^m$ p. m., there was a decided fall in temperature, undoubtedly caused by the unconscious partial opening of the hands. The strain upon the wrists was relieved at $2^h 46^m$ p. m. by fastening a cotton strap about the arms above the elbows to prevent the hands from opening; after this the cavity gradually increased in temperature, the curves following essentially the same course. It required a long time for the cavity to attain body-temperature, and as the subject appeared to be uncomfortable, the experiment was discontinued before any opportunity was afforded to observe the parallelism of the three curves.

Fig. 21. Temperature curves for experiment of January 12, 1911, with F. A. R.

The measurements of the body-temperature are given in fig. 21, the designation for the rectal curve being the same as usual, those for the hands being H_c and H_r for the thermometers in the center of the palms and at the base of the second finger, respectively.
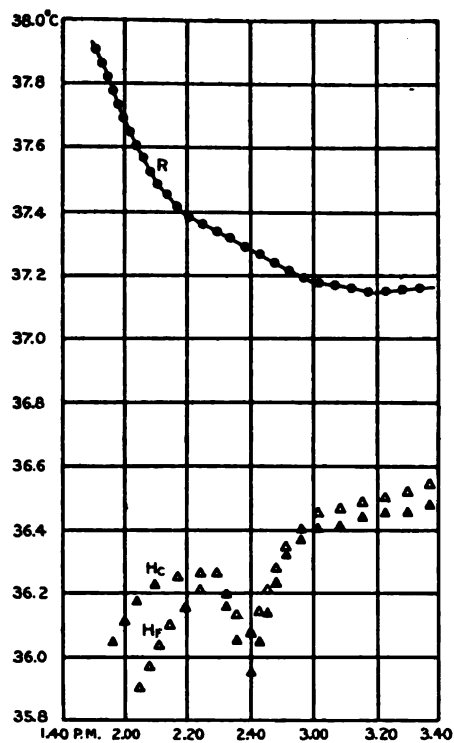
Experiment of January 13, 1911, *with V. G.*—In this experiment, a thermometer was used in the rectum at a depth of 9.5 centimeters; also, as in the previous experiment, a thermometer was placed in the center of the palms and another at the base of the second finger, with the hands clasped and tied with bandages. The space between the hands was warmed for 5 minutes before the experiment by a hot-water bottle at a temperature of 40° C.

During the experiment the subject occasionally fell asleep, but sat quietly the remainder of the time. The two thermometers in the hand gave readings which agree very well with each other, and while the parallelism with the records of the rectal thermometer is not perfect, there was a tendency for the temperature of the hand to fall as the temperature in the rectum fell. The slight rise between 3^h 19^m p. m. and 3^h 41^m p. m. indicated by the curve for the rectal thermometer is also seen in the curves for the thermometers in the hand.

The measurements for this experiment may be found represented in fig. 22, with the designations of the curves as for previous experiments.
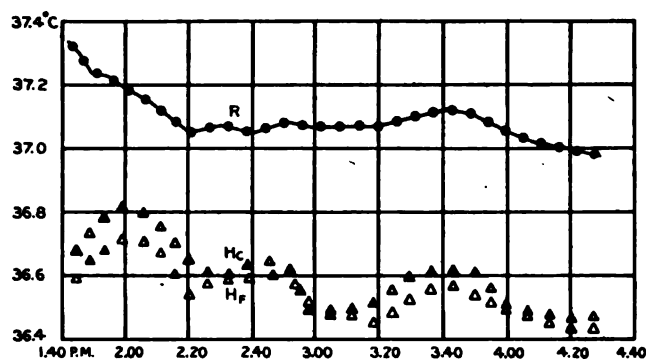
Fig. 22. Temperature curves for experiment of January 13, 1911, with V. G.

Experiment of January 14, 1911, *with C. H. H.*—In this experiment the subject sat in the chair, and both the deep and the shallow rectal thermometers were used, the former inserted to the depth of 9.5 centimeters, and the latter 6 centimeters. The temperature of the hands was taken by two thermometers as in previous experiments, the hands being clasped and bandaged as usual. Still another thermometer was placed between the crossed legs above the knees. No hot-water bottle was used.

The initial fall in the rectal temperature, noted in practically all of the experiments, is here very well marked. The curves representing the temperature in the hands remained fairly parallel throughout, but did not follow the curve of the rectal thermometer. On the other hand, the temperature of the upper leg, while requiring a very long time to reach equilibrium, followed the rectal temperature with remarkable constancy and accuracy when it had finally reached the upper level. An effort was made in other experiments to measure the body-temperature between the crossed legs, but these attempts

were unsuccessful, and the locality does not appear favorable for such observations, as its use involves much discomfort to the subject.

The records obtained in this experiment are given in fig. 23, the curves being designated as usual, that for the artificial cavity between the crossed legs being marked L.
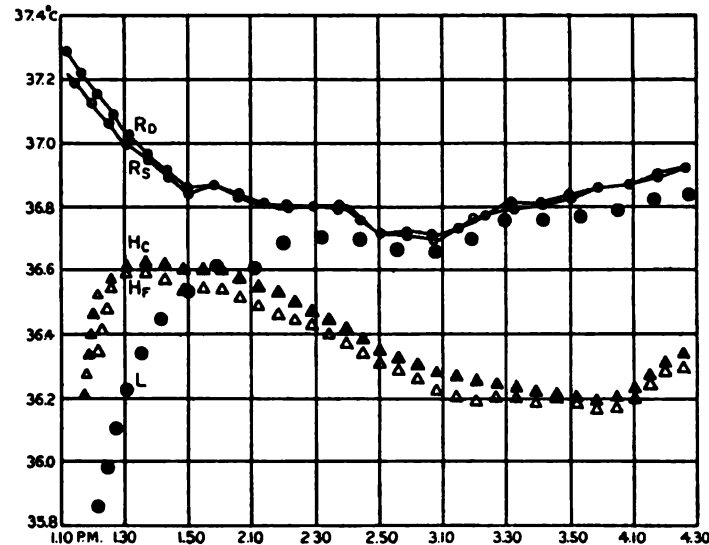
Fig. 23. Temperature curves for experiment of January 14, 1911, with C. H. H.

Experiment of January 16, 1911, *with Mrs. B—l.*—The deep and shallow thermometers were used in the rectum, inserted 7.5 centimeters and 4 centimeters respectively, and a single thermometer in the vagina at a depth of
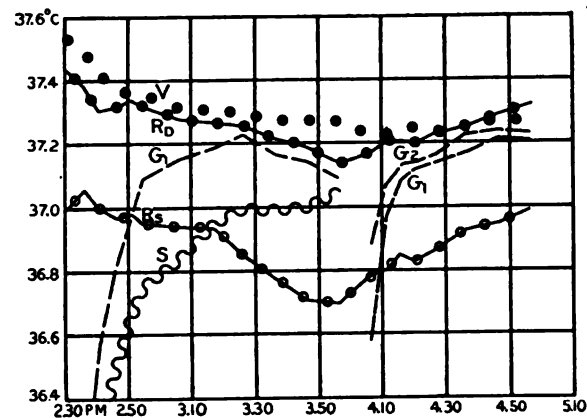
Fig. 24. Temperature curves for experiment of January 16, 1911, with Mrs. B—l.

10 centimeters. A thermometer was also placed in the left groin. At the beginning of the experiment a thermometer was strapped between the arm and the breast, but the temperature for this locality was very slow in reaching

constancy and the thermometer was later removed, and two thermometers were placed side by side in the left groin.

The usual initial fall in temperature on lying down on the couch is well shown in the curves for the deep and shallow rectal thermometers and for the vaginal thermometer. The temperatures for these three localities followed one another with fair constancy throughout the whole test. The groin temperature required considerable time to reach constancy, but thereafter followed the fluctuations in the temperature of the rectum and the vagina with reasonable regularity. As will be seen by the curves, the thermometers used in the latter part of the experiment for obtaining the temperature of the groin agreed fairly well with each other, and also followed closely those of the rectum and the vagina. While the temperature indicated by the shallow rectal curve is considerably lower than that of the deep rectal curve, it is interesting to note that the parallelism of the two records is very marked.

The records for this experiment are given in fig. 24; the curves are designated in the usual manner, the curve for the thermometer between the arm and the breast being marked S, and those for the groin, G_1 and G_2.

Experiment of January 17, 1911, *with Mrs. B—l.*—In view of the parallelism shown in the previous experiment between the groin temperature and the temperatures of the rectum and the vagina, this experiment was designed to
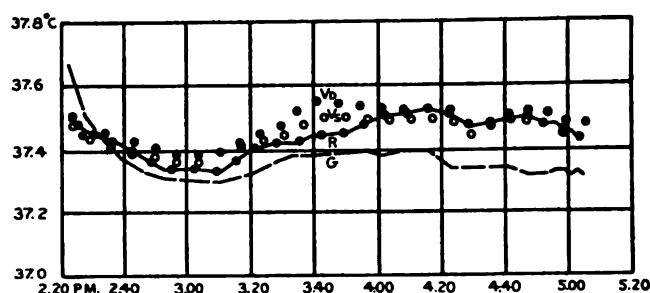
Fig. 25. Temperature curves for experiment of January 17, 1911, with Mrs. B—l.

make a comparative study of the temperatures of the groin, the deep and the shallow vagina, and the rectum, a thermometer being placed in all of these localities. In the rectum, the thermometer was inserted to a depth of 7 centimeters, while in the vagina, one thermometer was inserted to the depth of 10 centimeters, and the other to the depth of 6.5 centimeters. Before the experiment began, a hot-water bottle at a temperature of 42° to 43° C. was placed in the groin for 5 minutes. From the curves, it may be seen that the groin temperature was at first considerably higher than normal, then fell off until it reached a constant level somewhat below that of the vagina and the rectum, and thereafter followed in a general way the fluctuations of the other thermometers.

The records of the experiment may be found in fig. 25, with the curves designated as usual.

Experiment of January 20, 1911, *with C. H. H.*—In this experiment the subject crossed his arms on his chest, and one thermometer was placed between the lower arm and the chest, and another at the point where the arms crossed. In addition, two thermometers were used in the rectum, and one in each of the axillas, 6 thermometers in all being used. The thermal junctions were kept in position in the usual way by bandages. The locations between the crossed arms, and between the arm and the chest are particularly unfavorable for accurate records of body-temperature, as it is difficult to secure a perfect closure. The curves, however, seem to follow one another very fairly, this doubtless being due to the care exercised by the subject not to displace the thermometers. No hot-water bottles were used for preheating any of the cavities, and consequently the length of time required for the different parts to reach equilibrium is very well shown by the rise in the temperature curve at the beginning of the experiment. The usual initial fall of the deep and the shallow rectal temperatures is shown in this experiment. Between $3^h 17^m$ p. m. and $3^h 22^m$ p. m., the legs were uncovered in an attempt to produce a lowering of the temperature by exposing the skin surface, but this was without appreciable effect.

Fig. 26. Temperature curves for experiment of Jan. 20, 1911, with C. H. H.; 3.17 p. m. to 3.22 p.m., body surface exposed.

The records of the measurements are given in fig. 26, the curves being marked as usual. The curve for the thermometer between the arm and the chest is designated by S_1 and the curve for the thermometer at the point where the arms crossed by S_2.

Experiment of January 23, 1911, *with C. H. H.*—In this experiment the deep and shallow rectal thermometers were used to give a base line for comparison with the records of thermometers inserted in the right and the left axillas between the crossed arms, as in the previous experiment, and in the mouth. The thermometers in the rectum were inserted 12 centimeters and 8.5 centimeters respectively. The subject lay on a couch on his right side, the thermometers in the axillas being held in position by bandages as usual.

At $10^h 08^m$ a.m., the subject became uncomfortable, and lay on his back instead of on his right side. Between $10^h 22^m$ a.m. and $10^h 27^m$ a.m., the legs were uncovered to find if exposure would lower the temperature. As a matter of fact, the curves indicate a slight rise in temperature instead of a fall. The temperature in the left axilla quite closely parallels that in both the rectum and the mouth. The abnormal course of the temperature in the right axilla

and between the arms can be readily explained by the difficulty in securing a proper position on account of the discomfort of the subject. It is of interest to note that from $10^h 20^m$ a. m. to 11 a.m., the temperature between the arms (curve M) followed almost exactly that of the rectum.

The records of the measurement may be found in fig. 27, the designations of the rectal and axillary curves being as usual. The curves for the thermometers between the crossed arms and in the mouth are marked S and M, respectively.
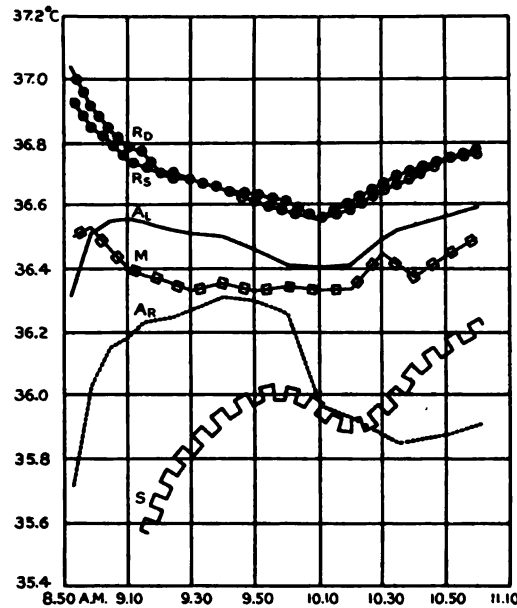
Fig. 27. Temperature curves for experiment of January 23, 1911, with C. H. H.; 10.22 a. m. to 10.27 a. m., body surface exposed.

Experiment of January 24, 1911, with J. J. C.—The conditions of this experiment were essentially the same as in the experiment of January 23, save that a different subject was chosen and the thermometer between the arms was omitted. Two thermometers in the rectum were used at a depth of 8 centimeters and 4.5 centimeters, respectively, one in each of the axillas, and one in the mouth. The subject slept much of the time during the experiment, and there was consequently so much trouble in securing a proper closure of the mouth that at $9^h 31^m$ a. m. the mouth thermometer was removed and replaced at $9^h 44^m$ a.m. surgeon's plaster being used to hold the lips together. At $9^h 46^m$ a.m., the subject changed his position and lay more on his side. Between $10^h 59^m$ a. m. and $11^h 03^m$ a.m., he drank $2\frac{1}{2}$ cupfuls of hot coffee, the thermometers in the mouth and the axillas being removed for this purpose. The subject then turned on his side and the thermometer was replaced in the left axilla. The thermometer in the mouth was likewise replaced, surgeon's plaster being again applied. Near the end of the experiment, there were indications that the shallow rectal thermometer was closer to the anus than was reported by the subject; the wide discrepancies between the records of

the two rectal thermometers from $11^h 10^m$ a. m. to $11^h 59^m$ a. m. can hardly be explained in any other way. Similarly, at the beginning of the experiment a temperature difference of approximately 0.6° C. between the two rectal records appears to be due to the fact that the shallow rectal thermometer was not inserted to so great a depth as was supposed.

The measurements of the temperature are shown in fig. 28, the curves being marked as in previous experiments.
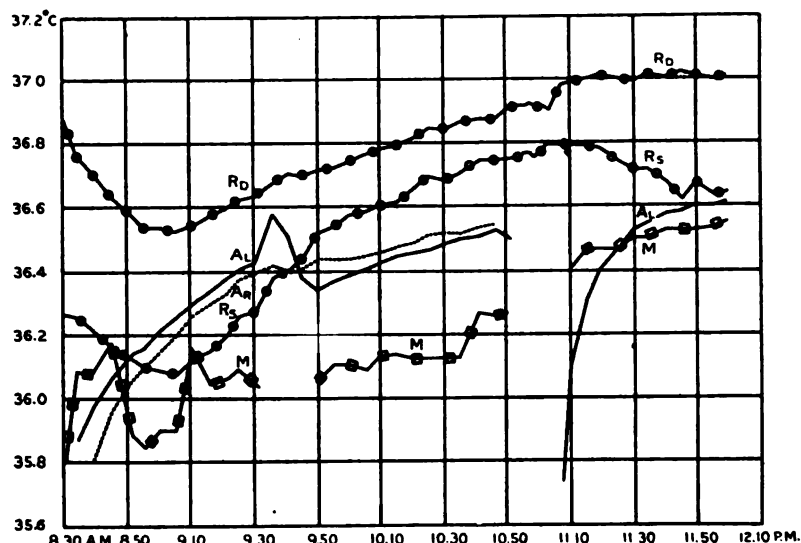
Fig. 28. Temperature curves for experiment of January 24, 1911, with J. J. C.; 10.59 a. m. to 11.03 a.m. drinking hot coffee.

Experiment of January 27, 1911, *with Mrs. B—l.*—In this and all succeeding experiments, compressed air was used to stir the water in the Dewar flask in the constant-temperature oven.

Two thermometers were used in the vagina, at a depth of 10 and 6.5 centimeters, respectively, and a thermometer in the rectum at a depth of 6 centimeters. In addition, a thermometer was placed in the groin and one in the right axilla, and intermittent observations were made in the mouth.

The curves for this experiment are interesting in that they show a period of 3 hours in which the temperature in the vagina and the rectum did not change more than approximately 0.1° C. The deep and shallow thermometers in the vagina remained within 0.07° C. of each other throughout the whole test, the records with the deep vagina thermometer being somewhat higher than those with the shallow thermometer. The rectal temperature was slightly higher than the vaginal temperature, the maximum deviation from the temperature of the deep vagina being 0.07° C. It was observed that during this experiment the rectal thermometer was embedded in feces. The thermometer in the groin required about 20 minutes to reach constancy. The curves for both the axilla and the groin temperatures follow in a general way the parallel temperatures of the deeper thermometers, although the temperature fluctua-

tions throughout the whole test were not sufficiently striking to make these records of very great value in this connection. The records of the mouth temperature are chiefly of interest as indicating the time required to warm the cavity to approximate constancy. With the mouth closed about 10 minutes prior to taking the temperature (see the curve at about $4^h 29^m$ p.m.), constancy was reached in about 8 minutes. With the mouth open for 10 minutes previous to taking the temperature, a period of over 15 minutes was required (see the curve at about 5 p.m.).

The records of body-temperature may be found in fig. 29, the curves being designated as usual.
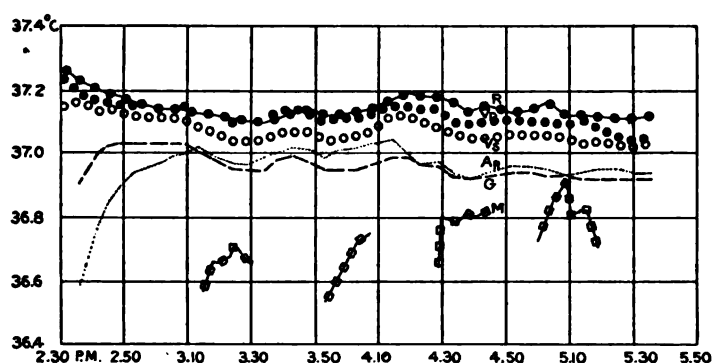
Fig. 29. Temperature curves for experiment of January 27, 1911, with Mrs. B—l.

Experiment of January 31, 1911, *with Mrs. B—l.*—In this experiment the temperature was taken in the vagina with the deep and the shallow thermometers; in the rectum with a single thermometer, also in the groin, and in either the right or the left axilla, no hot-water bottle being used for preheating the artificial cavities. An attempt was also made to secure the temperature of the mouth from time to time throughout the day, the subject being asked not to breathe through the mouth previous to the observations.

At the beginning of the experiment, the thermometer in the right axilla was not in proper position, and it was accordingly readjusted at $9^h 58^m$ a. m. When this temperature had attained the maximum, however, it remained fairly constant. At $11^h 58^m$ a. m. the subject changed from the couch to a chair, and sat quietly reading, except between $1^h 04^m$ p. m. and $1^h 29^m$ p. m., when she ate a dinner consisting of steak, coffee, and potato chips. At $3^h 25^m$ p. m. she lay down again on the couch and remained either sleeping or lying quietly awake for the rest of the experiment. During the time she sat in the chair, the thermometer was placed in the left axilla, and that in the groin removed. When she again lay down on the couch, however, the thermometers were returned to their original positions.

The curves for the deep and the shallow vaginal temperatures and for the rectal temperature follow one another throughout the day with remarkable regularity for the most part. The groin temperature required a long time to reach the maximum, but thereafter the records followed those for the rectum

and the vagina. On changing the thermometer to the left axilla, considerable time was required for the temperature to reach the maximum, and this was also the case when the right axilla was again used after the subject lay down on the couch in the afternoon. The records of mouth temperature are of value only for showing the length of time required to reach the maximum; the highest point in the curve should be taken to indicate the actual temperature of the mouth, an imaginary curve joining these high points conforming to the general shape of the curves for the deep thermometers. The tendency for the curves to rise throughout the day, even when the subject lay on the couch, is characteristic of the diurnal variation in which the highest temperature is in the late afternoon.

The curves showing the body-temperature for the different localities may be found in fig. 30.

Experiment of February 3, 1911, *with Mrs. B—l.*—The deep and shallow vaginal thermometers were used in this experiment, inserted to a depth of 10 and 6.5 centimeters, respectively, also a single rectal thermometer at a depth of 8 centimeters. Thermometers were placed in the groin, in either the right or left axilla, and temperatures were taken intermittently in the mouth throughout the experiment. A hot-water bottle at a temperature of 44° C. was used in the axilla, and another with a temperature of 49° C. in the groin for about 5 minutes before the experiment, but this preheating was not so effective as usual in shortening the time required to secure constancy.

During the first part of the experiment the subject lay on the couch quietly reading. At 9ʰ 19ᵐ a. m. the axilla thermometer was placed in a better position, and later (at 11ʰ 24ᵐ a. m.), as the subject had been moving about considerably, it was again readjusted. At 12ʰ 14ᵐ p. m., the subject changed from the couch to the chair; at the same time the thermometer was changed from the right axilla to the left axilla, which had been previously heated by means of a hot-water bottle at a temperature of 46.5° C. The temperature of the left axilla fell for the first few minutes, indicating that the preheating had raised the temperature of the cavity somewhat above the normal. From 1ʰ 01ᵐ p. m. to 1ʰ 25ᵐ p. m. the subject was eating dinner. At 2ʰ 30ᵐ p. m. she lay down on the couch again, a hot-water bottle at a temperature of 47° C. being placed in the groin, and another at the same temperature in the axilla. In both instances the temperature rose considerably, but apparently the maximum temperature was reached in a much shorter time than in the earlier portion of the test. At 3ʰ 01ᵐ p. m., the lips were fastened together with surgeon's plaster in order to keep the mouth thermometer in place for continuous observation. The subject was asleep and moved about somewhat. At 4ʰ 24ᵐ p. m. she was asked to keep the mouth tightly closed. Finally the thermometer was removed from the mouth at 4ʰ 56ᵐ p. m. and reinserted without the use of plaster at 5ʰ 19ᵐ p. m. A higher temperature was then observed in this locality, which may have been due to a better closure of the mouth after the rest in the interval when the thermometer was not in position.

The peculiar feature of the curves in this experiment is the general uniformity of the records for the deep and the shallow vaginal thermometers and the rectal
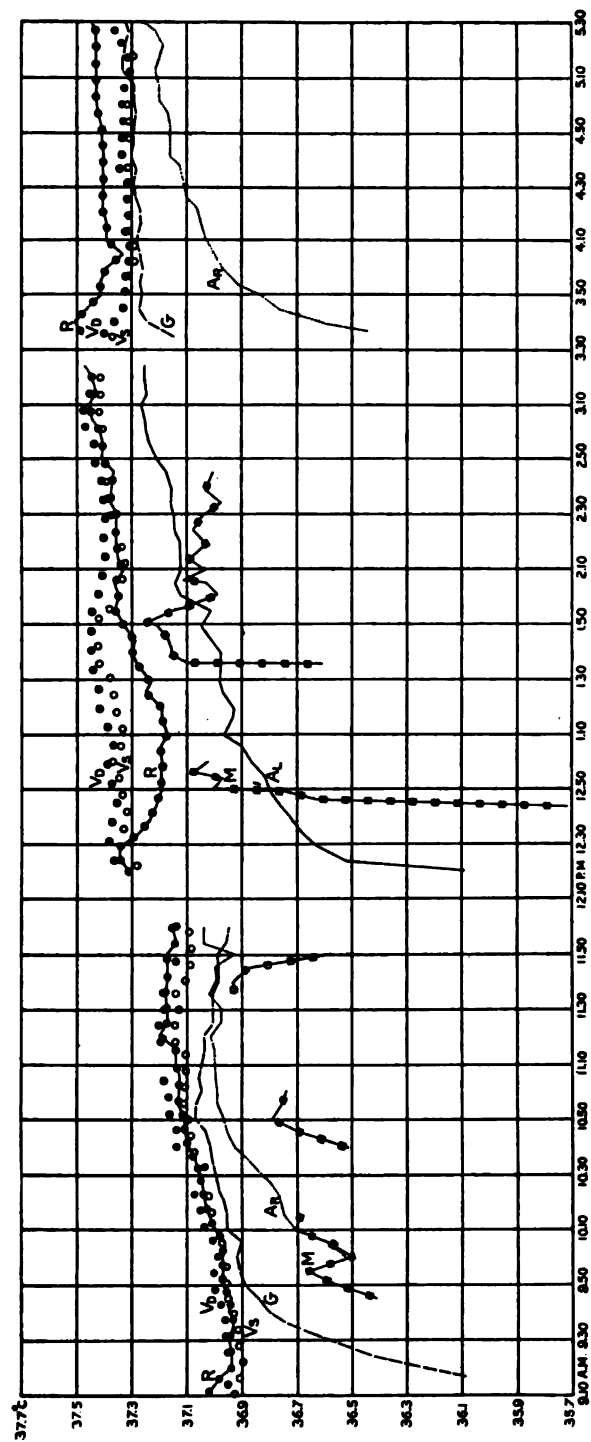
Fig. 30. Temperature curves for experiment of January 31, 1911, with Mrs. B—l. 1.04 p. m. to 1.29 p. m., eating.

thermometer, with the single exception of the record for the shallow vaginal thermometer between 2 p. m. and $2^h 30^m$ p. m. It would appear as if the thermometers in the vagina had been displaced during this interval, and that the shallow thermometer had slipped out of the cavity. The groin temperature followed with considerable regularity the temperature indicated by the other thermometers, while the inequalities of the axillary temperature in the early part of the experiment may be accounted for by the restless movements of the subject. The great irregularities in the temperature of the mouth accentuate the undesirability of this locality for such observations.

The curves showing the records of body-temperature may be found in fig. 31.

Experiment of February 6–7, 1911, *with Mrs. B—l.*—This experiment was planned to continue for 24 hours, in order to secure the total diurnal variation. The subject was lying on a couch during the whole experiment except when sitting in a chair between $11^h 59^m$ a. m. and $2^h 10^m$ p. m., and $5^h 24^m$ p. m. and $11^h 19^m$ p. m. A single thermometer was inserted in the rectum at a depth of 8 centimeters, and both deep and shallow thermometers in the vagina at a depth of 10 centimeters and 6.5 centimeters respectively. While the subject lay on the couch, temperature observations were made in the right axilla and in the groin. During the time the subject sat in the chair, the groin observations were discontinued, and the axillary temperature was taken in the left axilla instead of the right. Observations of the mouth temperature were made intermittently.

At the beginning of the experiment the groin and axilla were warmed by means of hot-water bottles at a temperature of 45° C. The temperature of the groin reached the maximum very shortly, but the temperature of the axilla required a long time to acquire constancy. An abnormal and wholly inexplicable rise in axillary temperature was noted, beginning at $10^h 39^m$ a. m. When the subject changed from the couch to the chair at $11^h 59^m$ a. m., the groin temperature records were discontinued and the temperature was taken in the left axilla instead of the right, so that the subject could use the right hand in eating. Before inserting the thermometer, the left axilla was heated with a hot-water bottle, at a temperature of 47° C., but gave very unsatisfactory results at first. The subject was asked to readjust the thermometer at $12^h 59^m$ p. m., and the results thereafter were much more uniform. Between $1^h 07^m$ p. m. and $1^h 32^m$ p. m. she ate her dinner, and at $2^h 12^m$ p. m., she returned to the couch. The groin and axilla were heated with hot-water bottles at a temperature of 47° C. before the thermometers were inserted, and the temperature of the groin rose considerably above even that of the rectum, cooling again rapidly to a constant temperature. The axillary temperature also quickly attained constancy. The subject was asleep between $3^h 17^m$ p. m. and $4^h 07^m$ p. m., and on waking up asked for water, drinking a half glassful at $4^h 12^m$ p. m. While it may have been a mere coincidence, all of the curves show a slight tendency to a lowering of the temperature after the drinking of the cold water. At $5^h 24^m$ p. m. the subject again changed from the couch to the chair, and the axillary temperature was taken in the left axilla, while the groin records were discontinued. During
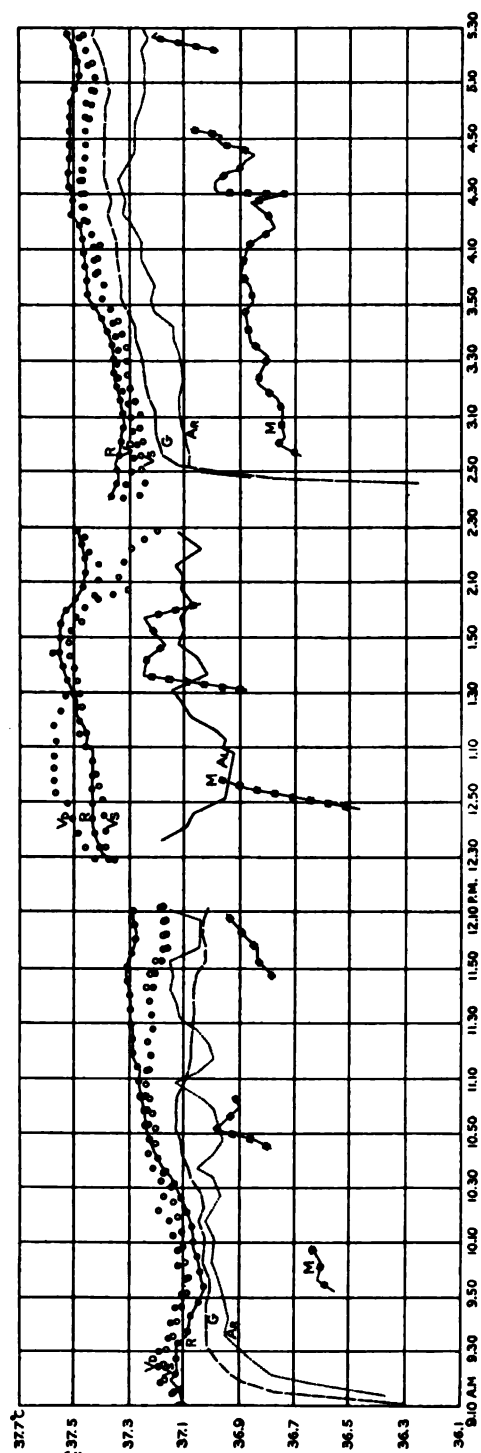
FIG. 31. Temperature curves for experiment of February 3, 1911, with Mrs. B——. 1.01 p. m. to 1.25 p. m., eating.

this period, the subject ate her supper. While she sat in the chair, the records were so irregular that they are not given. It is possible that the thermometers were not well located, as it was noted that a difference in temperature was caused by the subject sitting forward or back in the chair. At 11^h 19^m p. m. the subject changed from the chair to the bed, and beginning at 11^h 45^m p. m. the temperature curves are again given. The groin and right axilla were heated by means of a hot-water bottle at a temperature of 47° C. The groin temperature was noticeably affected by the preheating and rapidly attained constancy, but the temperature in the right axilla required the usual 20 minutes to reach a constant level. The subject lay very quietly the first of the night, and the temperature curves fell off in accordance with the general diurnal variation. From 1^h 30^m a. m. to 2 a. m. she moved about considerably, and also between 3 a. m. and 3^h 27^m a. m. At 3^h 27^m a. m. the subject was told that she need not keep the groin closed, and this temperature record was discontinued until 4^h 12^m a. m. She reported that she had slept at times. The subject moved more or less until about 5 o'clock, but she was very quiet from 5 a. m. until 5^h 30^m a. m. Later she moved somewhat and at 6^h 46^m a. m. asked several questions. The groin and axilla thermometers were removed at 7^h 14^m a. m., and the deep and the shallow vaginal thermometers at 7^h 52^m a. m. At 8 a. m. the thermometer was replaced in the groin, the groin and rectal temperatures being recorded continuously thereafter. The subject ate breakfast between 8^h 15^m a. m. and 8^h 39^m a. m., and from that time until the end of the experiment, at 9^h 27^m a. m., she was awake, talking and reading.

While the groin required considerable time to reach a constant temperature, except when preheated, when the body-temperature had finally been acquired the records followed with remarkable regularity those for the rectum and the vagina. The temperature of the axilla varied considerably and does not show the parallelism which would be expected, this parallelism evidently depending upon the accuracy and constancy with which the axilla is closed, thus accentuating very sharply the fact that the groin is on the whole a much better locality than the axilla for taking body-temperatures. The temperature observations made in the mouth show their usual irregularity, although a curve drawn through the maximal readings would follow the curves for the rectum and the vagina.

The curves showing the records of body-temperature may be found in fig. 32.

Experiment of February 27, 1911, *with J. J. C.*—In this experiment the deep and shallow thermometers were used in the rectum at depths of 9.5 and 6 centimeters respectively, and a thermometer in the left axilla. A thermometer was also inserted in the mouth and held there continuously.

During the experiment the subject sat in a chair, sometimes awake and reading and sometimes apparently asleep. At 9^h 23^m a. m. he drank some cold water. He changed his position in the chair at 10^h 33^m a. m., and the axilla thermometer was also readjusted at this time. At 11^h 16^m a. m. the left shoulder became uncovered, and at 11^h 22^m a. m. the subject removed his feet from the couch on which he had been resting them. From 12^h 21^m

Fig. 32. Temperature curves for experiment
of February 6-7, 1911, with Mrs. B—l.
1.07 p. m. to 1.32 p. m., eating; 4.12
p. m., drinking water; 8.15 a. m. to 8.39
a. m., eating.
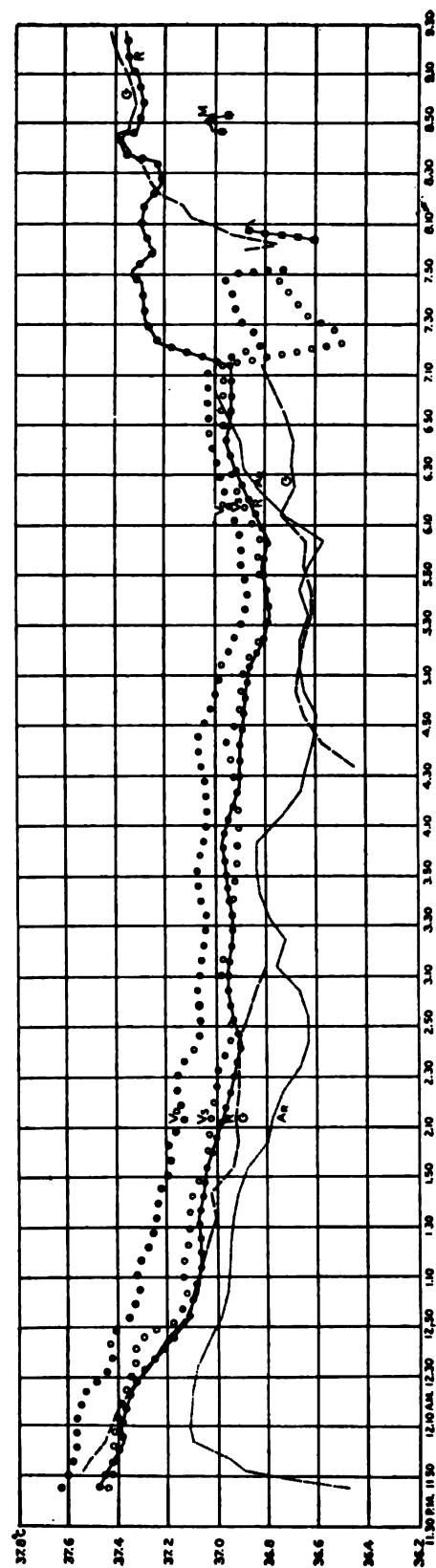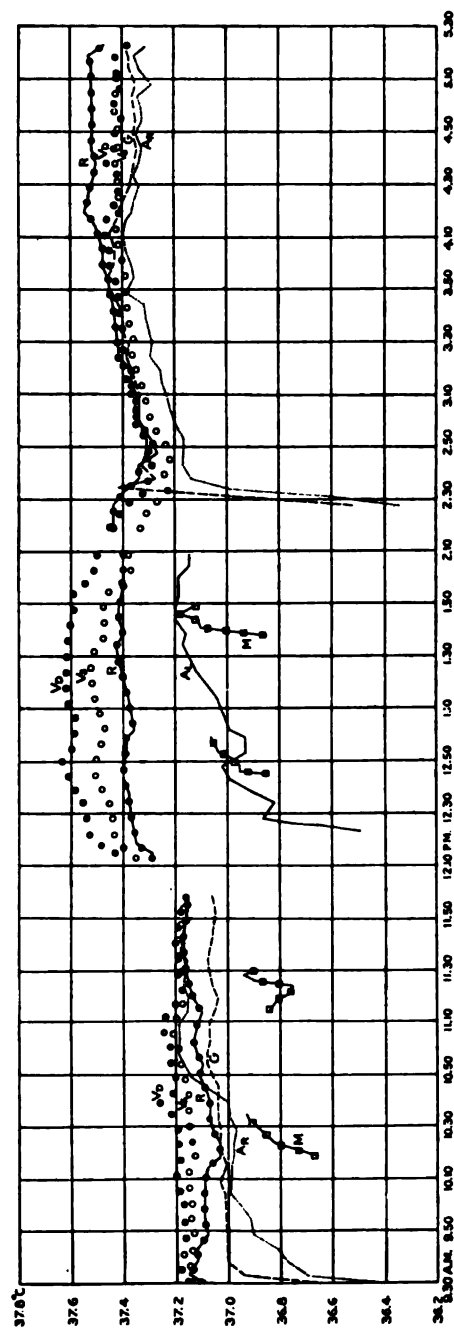
p. m. to 12ʰ 38ᵐ p. m. he was eating, the thermometers in the mouth and in the axilla being removed during this time.   Before reinserting the thermometer in the left axilla, the cavity was heated by a hot-water bottle at a temperature
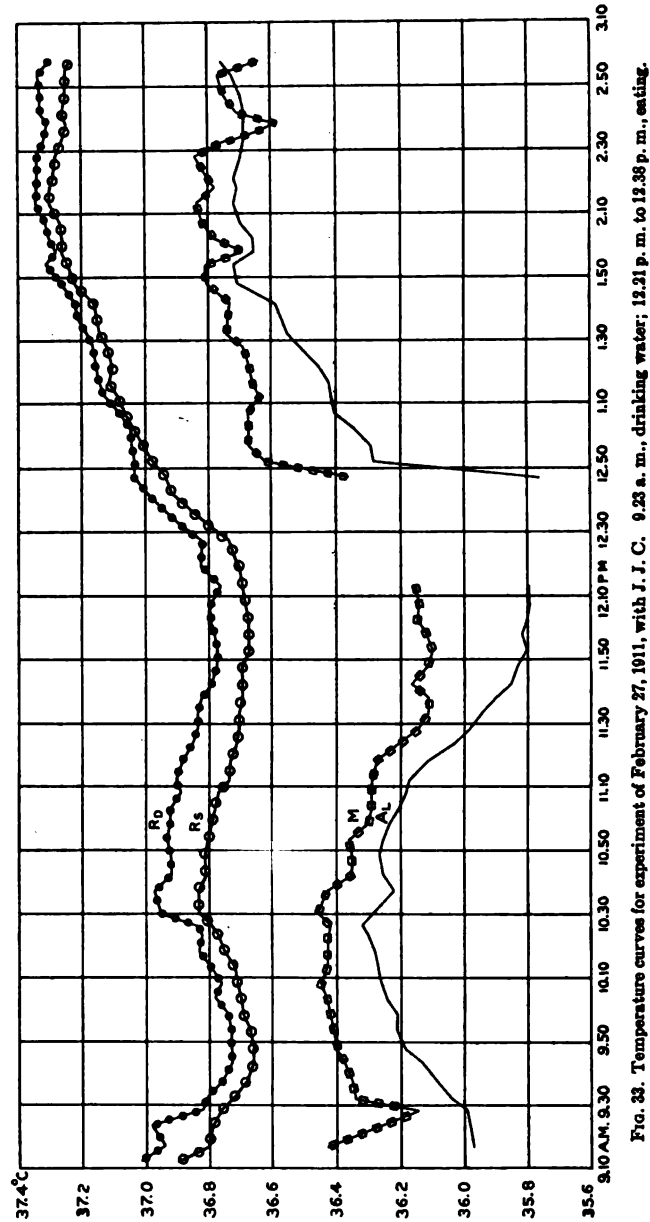
Fɪɢ. 33. Temperature curves for experiment of February 27, 1911, with J. J. C.   9.23 a. m., drinking water; 12.21 p. m. to 12.38 p. m., eating.

of 40° C.; this resulted in a rapid rise to constancy.   Toward the end of the experiment the subject became very tired and uncomfortable, and at 2ʰ 14ᵐ p. m. rested his feet on the couch again.

The general tendency toward parallelism of all of these curves is rather striking; nevertheless, the temperature of the mouth exhibits considerable fluctuation from time to time, and the temperature of the left axilla falls off more rapidly between 11^h 18^m a. m. and 11^h 48^m a. m. than do either the deep or the shallow rectal temperatures, these differences being more marked than in most of the experiments. The rapidity with which the temperature of the left axilla came to constancy after the use of the hot-water bottle at 12^h 47^m p. m. is also noticeable.

The measurements of the body-temperature are shown in fig. 33.

Experiment of March 1, 1911, *with C. H. H.*—The deep and shallow rectal thermometers were used in this experiment, with an insertion of 12 and 8.5 centimeters, respectively. A thermometer was also used in the left axilla, and one in the mouth. This experiment was designed to duplicate more or less the experimental conditions of the study made with J. J. C. on February 27. The mouth temperature was not taken continuously, however. A hot-water bottle at a temperature of 43° C. was used in the left axilla. The subject was eating between 12^h 37^m p. m. and 1^h 04^m p. m.; at 1^h 05^m p. m. he changed the position of his feet, resting them on a stool instead of on the couch.

The parallelism of the curves is very striking in all instances, the curve for the axilla, although showing a lower temperature, following the curves for the rectal temperature very satisfactorily.

The measurements of the body-temperature may be found in fig. 34.
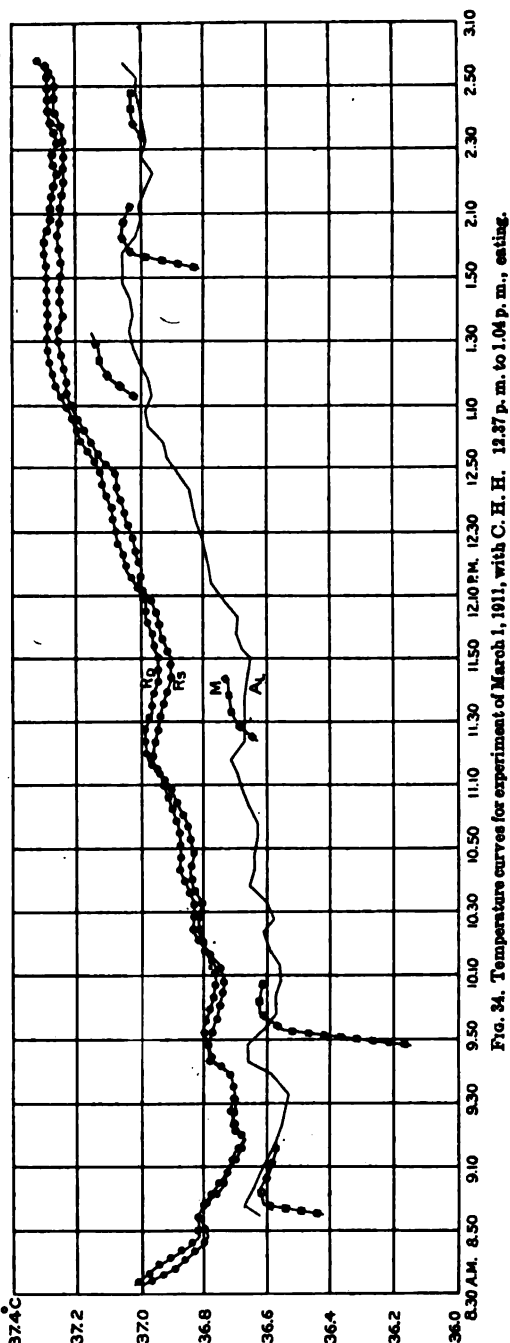
Fig. 34. Temperature curves for experiment of March 1, 1911, with C.H.H. 12.37 p.m. to 1.04 p.m., eating.

Experiment of March 2, 1911, with F. A. R.—The deep and shallow rectal thermometers were used, with an insertion of 12 centimeters and 8.5 centimeters respectively, and two thermometers in the hand, one in the center of the palms and one at the base of the second finger, the cavity between the hands having been previously heated with a hot-water bottle at a temperature of 42° C. Intermittent observations were also made of the mouth temperature. As in previous experiments, the hands were closely clasped, tied with cloth bandages, and covered with a pile of loose pieces of cloth. The arms were bound together above the elbows, as usual, to prevent the spreading apart of the wrists. At 8^h 58^m a. m. one of the hand thermal junctions was inserted a little farther toward the center of the hand. To test the effect of hot and cold drinks, the subject was given cold water at 9^h 48^m a. m. and a cupful of hot coffee at 11^h 08^m a. m.
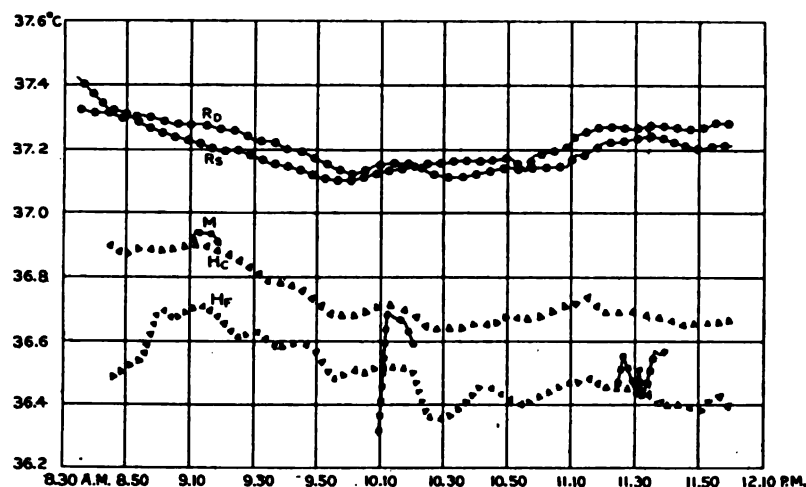
Fig. 35. Temperature curves for experiment of March 2, 1911, with F. A. R. 9.48 a. m., drinking cold water; 11.08 a. m., drinking hot coffee.

In a general way the curve for the thermometer in the middle of the hand follows the curve for the rectal thermometer, although in the latter part of the experiment the rise in temperature is not so noticeable as in the curve for the rectal thermometer. While the temperature curve for the thermometer at the base of the second finger shows wide variations, nevertheless the general tendency is not far from that shown in the curve for the thermometer in the middle of the palms. The temperatures taken in the mouth are very irregular and it is impossible to draw any deductions from the observations in this cavity. Just after taking hot coffee, a slight rise may be noted in all of the temperature curves, but the cold water appeared to have no effect.

The curves showing the measurement of the body-temperature may be found in fig. 35.

Experiment of March 3, 1911, with F. G. B.—In this experiment, the shallow and deep rectal thermometers were used, a thermometer in the left axilla, and one in the mouth. Before inserting the thermometer in the left axilla,

the cavity was heated by means of a hot-water bottle at 42° C. The subject sat in a chair throughout the experiment. From $2^h 55^m$ p. m. until $3^h 23^m$ p. m., he endeavored by muscular activity to stimulate a rise in temperature; he moved his legs and arms and exercised with a stool, lifting it, holding it at arm's length, and raising and lowering it above the head. He also placed a book rest on his toes, and moved it up and down. The exercise was sufficient to cause perspiration and fatigue. After the exercise, he was very quiet, closed his eyes, and tried to go to sleep. His elbows rested on the arms of the chair, and his head on his hands. At $3^h 41^m$ p. m., as the mouth thermometer was in position, some directions were written on a piece of paper. At $3^h 49^m$ p. m., 400 cubic centimeters of cold water at a temperature of 4.8° C. were taken. During the muscular work, the mouth thermometer was used, and held continuously in place until it was removed when the cold water was taken. It was then immediately replaced and allowed to come to the maximum temperature.
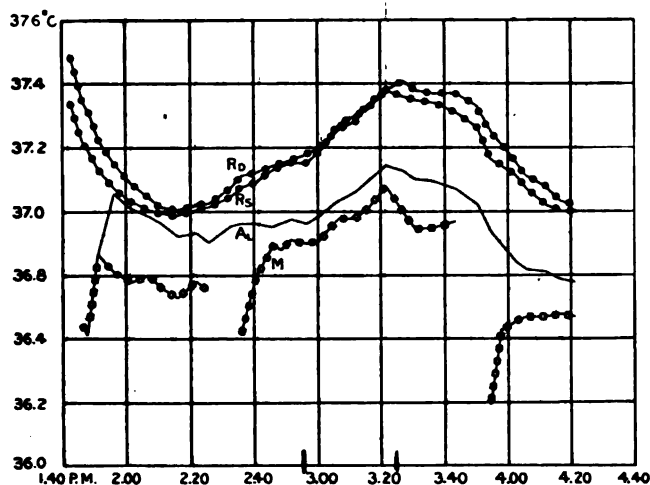
Fig. 36. Temperature curves for experiment of March 3, 1911, with F. G. B. 2.55 p. m. to 3.23 p. m., muscular exercises; 3.49 p. m., drinking cold water.

Special care was exercised by the subject to keep the mouth closed and to breathe only through the nose, so as to keep the mouth temperature as nearly constant as possible. Care was also taken not to disturb the position of the axillary thermometer. The curves for this experiment show remarkably well the uniformity between the deep and the shallow rectal temperatures, the temperature in the left axilla, and that in the mouth. The fluctuations during the muscular exercise, the succeeding quiet condition, and the taking of the cold water were almost exactly equal in all the curves and were clearly defined. As would be expected, the muscular exercise produced a rise in temperature, while the subsequent quiet condition and the taking of cold water evidently caused a lowering of the temperature.

The curves showing the body-temperature measurements for the different localities may be found in fig. 36.

Experiment of March 10, 1911, *with J. J. C.*—The deep and the shallow rectal thermometers were used at a depth of 15 centimeters and 11.5 centimeters, respectively. A thermometer was also placed in the left axilla, this cavity having been previously heated by a hot-water bottle at a temperature of 42.5°C., and intermittent observations were also taken in the mouth. The influence of muscular activity was studied in this experiment, and beginning at 3ʰ 26ᵐ p. m. the subject exercised quite vigorously. This activity appeared to tire him, as he breathed heavily and perspired freely. During the exercise he was more or less exposed, as he wore a blanket over his shoulders instead of a sweater. At 3ʰ 49ᵐ p. m. he stopped exercising and became quiet. For
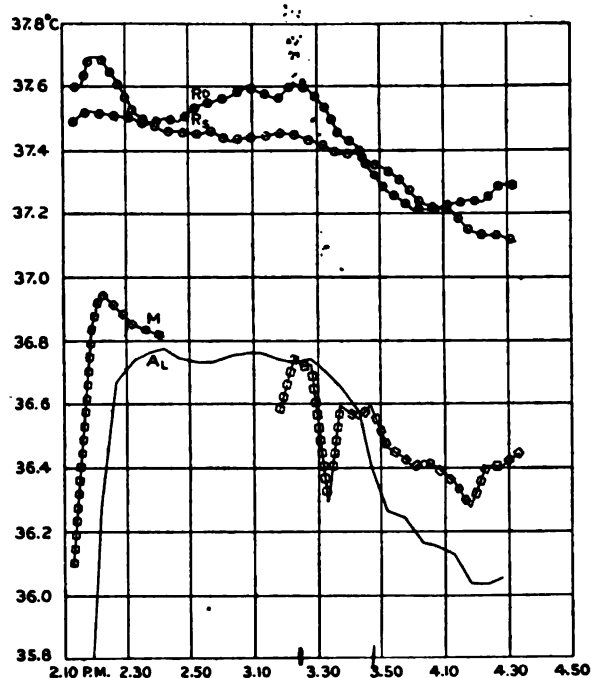
Fɪɢ. 37. Temperature curves for experiment of March 10, 1911, with J. J. C. 3.26 p. m. to 3.49 p. m., muscular exercise.

some unaccountable reason there was not a very close parallelism between the two rectal records, although all of the curves show a general tendency toward parallelism, especially the curves of the rectal and the axillary temperatures. The muscular exercise did not produce a rise in the temperature; while this is not easy to explain, it may have been due to the fact that the surface of the skin was more exposed during the exercise than when the subject was quiet, causing a tendency to cool the surface.

The curves showing the measurements of the body-temperature in the different localities may be found in fig. 37.

Experiment of March 13, 1911, *with F. A. R.*—In this experiment both deep and shallow rectal temperatures were taken, also the temperature of the left

axilla, and occasionally the temperature of the mouth. The two rectal thermometers were inserted at a depth of 10 and 6.5 centimeters respectively. The axilla was preheated by means of a hot-water bottle at a temperature of 42°C., which caused the subject to perspire; during the experiment the bandage holding the axilla thermometer loosened. In previous experiments it had been noted that the rectal temperatures usually fell at the beginning of an experiment, which would indicate that the temperature when the subject was active before the experiment was higher than after he became quiet. For this reason it was decided to take the mouth temperature at the very beginning of the experiment. If the curves indicating the mouth and rectal temperatures
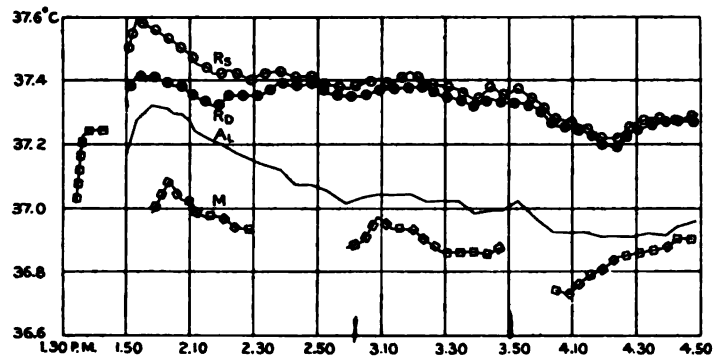
Fig. 38. Temperature curves for experiment of March 13, 1911, with F. A. R. 3.02 p. m. to about 3.50 p. m., muscular exercise; 3.50 p. m., drinking cold water.

are to be parallel, this first observation of the mouth temperature should be very high, and this was found to be actually the case. At $3^h 02^m$ p.m., the subject began to exercise by lifting a stool, and at $3^h 32^m$ p.m. he was still exercising but not working very hard. At $3^h 50^m$ p. m., just after he had stopped exercising, he drank a glass of cold water at a temperature of 10° C. A subsequent fall in temperature of almost 0.2° C. was noted, which may have been due in part to the influence of the cold water. The temperature curves for this experiment were in general parallel, the curves for the temperatures of the mouth and the rectum being more nearly parallel than usual.

The curves showing the measurement of the body-temperature in the different localities may be found in fig. 38.

CONCLUSIONS.

From this series of temperature observations made on a number of different subjects, certain definite conclusions have been drawn:

1. When two thermometers are placed in one internal cavity at not less than 6 centimeters deep, the temperature curves are parallel and approximately equal. This is shown in figs. 15, 20, 23, 25, 27, 29, 30, 31, 32, 33, 34, 35, 36, and 38, but certain abnormalities not easily explainable are seen in figs. 26 and 37.

2. When two thermometers are placed in one internal cavity and the distance between them is 3.5 centimeters, one being within 5 centimeters of the surface of the body, the curves obtained are parallel, but not equal in value, thus indicating a temperature gradient. See figs. 17, 19, 24, and 28.

3. Thermometers placed in the rectum and the vagina, at depths of at least 6 centimeters, show curves that are parallel and approximately equal. See figs. 16, 18, 24, 25, 29, 30, 31, and 32.

4. Thermometers in the right and left axillas give curves that are parallel, showing approximately equal temperatures. This is indicated in figs. 15, 17, and a part of 19, also in 20 and 26. Exceptions to this are shown in figs. 18, 27, and 28, but in considering these exceptions one must not lose sight of the fact that it is very difficult to secure constant and well-closed axillas undisturbed by body movements; we have every reason to believe that the conflicting results in these three curves are due to misplaced thermometers.

5. Two thermometers placed in the groin give results that are parallel and approximately equal. This is shown in fig. 24.

6. Two thermometers placed in the hand give results that are equal and parallel. See figs. 21, 22, and 23. In fig. 35, the curves are parallel but not equal, indicating a slight gradient.

7. The use of the hot-water bottle hastens the warming-up of such artificial cavities in the body as the axilla, groin, and hand. This fact is shown in figs. 19, 20, and 22, and in parts of 31, 32, and 33, also in 34, 35, 36, 37, and 38.

8. When lying on a couch after the slight muscular work involved in coming to the laboratory and moving about before the experiment, there is usually an initial fall of internal temperature. This is clearly evident in figs. 15, 19, 20, 21, 22, 23, 24, 26, 27, 28, 33, 34, 36, and 37, but not so well shown in figs. 17, 18, 25, 29, 30, and 35, and is entirely absent in figs. 16, 31, 32, and 38.

9. Temperatures taken in the mouth are in general extremely irregular and unsatisfactory, as may be seen in figs. 28, 29, 30, part of 31, and 32, also in fig. 35. Nevertheless fair results are shown in figs. 27, 33, and 34, and very satisfactory results in figs. 36 and 38.

10. The effect of eating a meal tends to increase somewhat the temperature of the body. See figs. 17, 30, 31, 32, 33, and 34.

11. On exposing portions of the skin under the conditions of the experiments here made, no effect on body-temperature was apparent in figs. 26 and 27.

12. On drinking hot coffee, the body temperature was very slightly increased. This is shown in figs. 28 and 35.

13. Drinking cold water had a tendency to lower the body-temperature. See figs. 36 and 38. This effect was not evident in the experiment represented by fig. 35, however.

14. Muscular exercise produced a marked increase in body-temperature in at least one experiment (see fig. 36), but was without effect in others (see figs. 37 and 38). Of significance was the fact that while obtaining the data for fig. 37, the skin of the subject was more or less exposed to the air.

15. The internal temperature of the body and that of the axilla, breast, groin, hand, arm, and mouth, have a tendency toward parallelism. This is evident in practically all of the curves, but is especially well shown for the internal temperature and the axilla in figs. 20, 27, 33, 34, 36, and 38, although in fig. 27 this is not true of the right axilla for reasons previously explained. The parallelism is also shown for the internal temperature and the groin in figs. 24, 25, and 31; for the internal temperature and the mouth in figs. 27, 33, 34, 36, and 38; and for the internal temperature and the upper leg in fig. 23.

Finally, it can be stated that an examination of all the results obtained shows in the temperature curves a remarkable trend toward parallelism, a parallelism that would be exact, there is every reason to believe, if the thermometers could remain in precisely the same position and if the cavities could remain absolutely constant in their closure. We feel justified, therefore, in summing up this work by stating that, aside from the skin temperature, a rise or fall in rectal temperature is accompanied by a corresponding rise or fall in temperature of all other parts of the body.

NUTRITION LABORATORY, CARNEGIE INSTITUTION OF WASHINGTON,
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FEEDING EXPERIMENTS WITH ISOLATED FOOD-SUBSTANCES.

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FEEDING EXPERIMENTS WITH ISOLATED FOOD SUBSTANCES.

Although the proteins have long had attention centered upon them because of their commanding position in relation to nutrition, it is only in very recent years that the progress of chemical investigation, fostered by the introduction of new methods of research, has begun to make our conception of these fundamentally important substances more exact. The role of the nitrogenous substances in both plants and animals has gradually been brought to light by a series of effective researches; but even to-day it is still common, despite the newer knowledge in the field of biochemistry, to read of the part played by proteins, fats, and carbohydrates in nutrition, as if these groups of compounds were each chemically homogeneous and, within wide limits, physiologically interchangeable. Not only have these food-stuffs been discussed in the past without more than the scantiest consideration of possible specific differentiations within the individual groups, but in nearly every investigation on nutrition the nutrients have been employed in those complex and often little-understood mixtures which make up the common foods.

That any such indefinite combination of known and unknown organic compounds is an unsatisfactory and unideal starting-point in any adequate study of the laws of nutrition was appreciated by Carl Voit, the foremost student of this subject of the past generation. In discussing the necessity for an accurate knowledge of the food intake in the study of metabolism he says:

Zu dem Zwecke wäre es unstreitig am besten, könnte man nur reine, chemische Verbindungen (die reinen Nahrstoffe) z.B. reines Eiweiss, Fett, Zucker, Stärkemehl, Aschebestandtheile, oder Gemische derselben geben. Da aber die Menschen und auch die Thiere nur selten solche geschmacklose Gemenge auf die Dauer aufzunehmen oder zu ertragen vermögen, so bleibt für die meisten Fälle nichts anderes übrig als schon durch die Natur zusammengesetzte Mischungen (die Nahrungsmittel) zu wählen. Jedoch wäre es wohl möglich und ganz verdienstvoll, die Grundversuche, nachdem vorher der Weg mit Hilfe der letzteren Mischungen gefunden worden ist, mit den reinen Stoffen zu wiederholen, obwohl sich dabei sicherlich im Wesentlichen keine anderen Resultate ergeben werden.*

* C. Voit: Hermann's Handbuch der Physiologie, 1881, vi, (1), p. 19.

Judging on the basis of such information as was available at the time when the preceding was written, Voit further stated in regard to the proteins:

Die verschiedene Modificationen des Eiweisses haben höchst wahrscheinlich sämmtlich ganz die gleiche Wirkung auf den Stoffumsatz, jedoch liegen hierüber noch keine genauen Untersuchungen vor.*

Certain exceptions to the assumed physiological equivalence of the proteins of various origins have long been known, conspicuously in the case of gelatin. This nitrogenous compound, possessing many of the most characteristic chemical features of a typical protein, was found to be inadequate as the sole source of nitrogen to the higher animals. Its lack of a constituent tyrosine complex and of sulphur was appreciated; and to this was often charged the insufficiency of its nutritive functions. It has remained for the newer researches on the proteins—those interesting studies of the past ten years which have unraveled so much of the structural complexity of the albuminous molecule—to raise new questions and place the problems of nutrition in a new light. It has been the structural dissimilarity rather than the likeness of the proteins which has aroused physiological comment. The rich fund which these investigations of the constituent amino-acid derivatives of the various proteins of both animal and plant origin have disclosed need not be presented here.† The more striking findings are rapidly becoming a matter of common knowledge in physiological circles. Thus it is appreciated that the zein of maize and the gliadin of wheat show distinctive features in respect to the yield of the different amino-acids obtainable from them. Zein is distinctly deficient in comparison with most other proteins: it yields no tryptophane, glycocoll, or lysine. Gliadin is characteristically rich in the glutaminic acid complex. Other equally interesting illustrations might be cited.

Are these different proteins, specific in respect to origin, biologically differentiated and individually unique in chemical make-up, of equal value for the purposes of nutrition? If they are not, how are we to explain the uniformity, apparent or real, which is exhibited in the composition of the individuals of any species living under widely divergent dietetic conditions? The flesh-eater and his herbivorous neighbor accumulate specific muscle-proteins, blood-proteins, and brain-proteins despite recognized differences in the nitrogenous intake.

The problem here presented has been both simplified and complicated by the trend of recent studies in the chemistry of digestion.

* C. Voit: Hermann's Handbuch der Physiologie, 1881, VI (1), p. 104.

† Elaborate reviews of this subject will be found in the monographs by Plimmer, Schryver, and T. B. Osborne, in the series of Monographs on Biochemistry, Longmans, Green & Co.; also Die Pflanzenproteine, Ergebnisse der Physiologie, 1910, X, pp. 47–215.

So long as it was still assumed that the proteins are only slightly modified within the alimentary tract, it was not easy to appreciate how these widely differing amino-acid complexes could be converted into a common protein or group of proteins. But with the introduction of the evidence that proteins experience a profound cleavage prior to absorption—that the organism is equipped with an outfit of enzymes easily capable of effecting such intense hydrolyses, and that the proteins in all probability normally disappear from the alimentary tract as amino-acid fragments and relatively simple polypeptides— our conception of protein assimilation has changed notably.

It is, perhaps, too early yet to determine to what extent the theories of protein metabolism and reconstruction, which Loewi and Abderhalden in particular have championed, accord with the facts of experience. Whether the organism synthesizes blood and tissue proteins from the amino-acid rests of digestion, and thus only; whether there are no rearrangements whereby one amino-acid may give rise to another; and whether under these circumstances the synthetic power of the organism is limited to a choice by the minimum of all essential protein building complexes—the so-called "Bausteine"—can not yet be profitably debated in detail.

The problem of protein synthesis is further complicated by a consideration of the activities of bacteria in relation to the food-products which enter the alimentary tract. It is now well appreciated that microorganisms grow and die in large numbers throughout the lower parts of the digestive tube, so that it is not uncommon to find the fæces to be composed in a very considerable degree of the bodies of dead bacteria. It is not unlikely that the organisms which thus perish in the intestinal canal are subject to autolytic or other digestive degradation by which their protoplasmic constituents may become available as food sources to the organism of the host. Bearing in mind the synthetic possibilities inherent in plant cells, such as bacteria represent, it is by no means beyond the bounds of reasonable interpretation to assume that the amino-acids first formed by digestion of food proteins may experience a synthesis into new forms of protein complexes prior to a subsequent digestion and utilization. Viewed in this light, the immediate hydrolysis products of our foodstuffs may become available only after they have been in greater or less part reconstructed by these preeminently synthetic symbiotic bacteria into products of more uniform character, possibly widely different from the original intake. Nucleoprotein synthesis, for example, may thus become referable to bacterial intervention.

No one can say at the present time to what extent, if at all, such synthetic possibilities enter into the problems here discussed. The subject has recently again been referred to by Lüthje.* The

*Lüthje: Ergebnisse der Physiologie, 1908, VII, p. 826.

important point for us is that we must deal with such possibilities; we must plan and interpret our nutrition experiments to-day in the light of these newer ideas.

If we accept the synthetic theory of metabolism, disregarding the cooperation of bacteria, it becomes possible to understand how the lack of some fundamental unit, like tyrosine, tryptophane, lysine, or cystine may lead to malnutrition or death through the inability of the organism to construct normal protein and normal protoplasm, because of a deficit of essential structural complexes. The errors of a one-sided diet present a new point of view. The importance of these theories is enormous, not alone for the nutrition of man but also for the welfare of our domestic animals. Rational and economical feeding is based upon a correct interpretation.

Considerations such as the foregoing certainly justify an extension of experimental work in nutrition along the lines suggested by the rapidly accumulating data on the structure of the individual proteins. The theories must be subjected to the rigorous test of experiment. The relative and absolute value of individual proteins must be determined by physiological trials as a preliminary to definite and more permanent, rational dietary programs. We have attempted the beginnings of such a study.

At the outset we were confronted by the fact that there are on record few, if any, successful experiments in feeding isolated foodstuffs. Still fewer are those in which the protein compound was fed isolated, in a reasonable degree of purity. By "successful" we mean experiments in which the health and vigor of animals were maintained under adequately controlled conditions for sufficient periods of time to permit of more than tentative conclusions. The total number of feeding trials in which the role of the protein food is in some way concerned is very large. We shall omit reference to all except those which bear specifically on the problems under consideration, viz., the significance of individual proteins in nutrition.

It may not be amiss at the outset to point out the broader requirements which any adequate dietetic régime involves and upon which its nutritive success depends in good measure. In the first place the nutrients must be presented in a form that is digestible and thus available for physiological utilization. The physical texture as well as digestibility *per se* plays an important part in this respect. Again, the available parts of the diet must be adequate in amount to cover the calorific needs of the organism to which it is supplied, *i.e.*, there must be sufficient metabolizable energy. One might be inclined to omit reference to such apparently obvious facts had they not been serious factors in previous experimental failures in feeding isolated food-substances. In recent years much emphasis has further been laid upon certain less evident considerations involving nutrition more

indirectly. Thus the question of the inorganic constituents of the diet is far from settled, and this aspect of dietetics can scarcely be said to rest upon any very rational basis. We realize the need of chlorine and phosphorus, of calcium and iron in certain vital functions; but the physiological requirement of other elements is none the less definite because it is not fully understood. On one point, namely, the power of the animal organism to employ the elements phosphorus and iron in the form of either organic or inorganic compounds, we have assumed that the consensus of opinion and the preponderance of experimental evidence are in favor of either possibility. The debate on this topic need not be reviewed here.

Closely related to these nutritive requirements is the subject of those food accessories which determine in large measure what is spoken of as the palatability of any ration. They act in manifold indirect ways to influence the digestion of the nutrients by their effect in promoting or retarding secretion into the alimentary tract; they affect the appetite and the psychic element in digestion—all of which have received attention anew through Pawlow's efforts. After all one is as yet not justified in insisting that these incidental features of the dietary are absolutely indispensable. Quoting Tangl:

> Eine fördernde Wirkung der sog. Reiz—oder Würzstoffe—sagt Kellner—auf die Ausnutzung des Futters ist bis jetzt bei keiner einzigen der auf diesen Punkt gerichteten Untersuchungen beobachtet worden. Dasselbe gilt nicht nur für die landwirtschaftlichen Nutztiere, sondern auch für den Menschen.*

The undoubted biological importance of that rather vaguely defined and hetereogeneous group of compounds known as lipoids has raised the question as to whether they are at all necessary in any complete diet, or whether they can be synthesized by animals as they are by plants. The lipoids (phosphatides and cholesterols) are present as common cell derivatives in every familiar food and can only be excluded by special, laborious methods of extraction. It is not strange, therefore, that there is a paucity of evidence relating to their absolute significance as constituents of the food-intake. Recent experiments by Stepp† on the indispensability of the ether-soluble constituents of the food for the life of mice are far from conclusive.

Lastly, it seems worth while to point out that the nutritive conditions which pertain during the period of growth are in many respects—perhaps far more than is realized—different from those existing at a later period. During the active constructive phase new material must be supplied which differs both in quality and amount from the quota furnished as a maintenance ration. We realize well enough that the growing skeleton requires calcium; but to what

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*Tangl: Oppenheimer's Handbuch der Biochemie, 1910, III (2), p. 55.
†Stepp: Biochemische Zeitschrift, 1909, XXII, p. 452.

degree are the further nutritive demands modified by developmental changes? Are the same proteins which suffice the adult capable of supplying the essential building-stones to the young? Here again a wealth of new problems still confronts us.

There are no recorded experiments on the larger animals, such as are commonly used in laboratory work, which furnish any conclusive data on the broader questions involved in this research. The careful experiments of Röhmann and his pupils* on dogs fed with isolated proteins (edestin, vitellin, casein, myosin) extended over 50 days as a maximum period in one case. Such investigations, as well as those of Abderhalden and his collaborators,† have yielded much of interest in regard to the utilization of the food-stuffs investigated and have given valuable hints for future work in nutrition. But the periods of observation have been far too brief to permit any permanent positive conclusions regarding the adequacy of the proteins fed. Minor deficiencies may fail to become conspicuous in even comparatively long periods in the case of animals whose size and span of life indicate a considerable store of reserve material.

For various reasons the most successful investigations in this field have been conducted on much smaller animals, especially rats and mice. The preparation of suitable pure food supplies on a scale sufficient for long periods and in economically procurable amounts is thereby rendered possible. The necessary scientific measurements and analyses can be conducted on a scale impossible for larger animals, and the problem of care and attention is equally simplified. Experiments can be duplicated without great effort and individual peculiarities eliminated by force of numbers. Furthermore, the various stages of growth and maturity are completed in the smaller animals within relatively short periods of time, so that the permanent effects of any dietary become apparent within a range of days or months that is not outside of ordinary experimental possibilities of observation. As illustrations of some of these features it may be recalled that the ultimate effects of complete inanition are apparent in four or five days in rats or mice; in dogs the fatal outcome may be delayed for many weeks. The duration of life in the white rat is about three years; about 280 days suffice to complete the entire period of growth to maturity.

To what extent, if any, the rigorous conditions, such as restraint in cages, etc., set by laboratory requirements may modify the normal physiological functions of the small animals is not apparent from such records as we have found. It should be noted that both rats

*Marcuse: Archiv f. d. ges. Physiologie 1896, LXIV; 1897, LXVII, p. 373.
 Steinitz: *Ibid*, 1898, LXXII, p. 75.
 R. Leipziger: Inaugural Dissertation, Breslau, 1899.
 E. Ehrlich: Inaugural Dissertation, Breslau, 1900.
 †Cf. papers by Abderhalden and collaborators in numerous recent volumes of the Zeitschrift f. physiol. Chemie.

and mice are reported to have been kept in health on milk alone during periods of six months or more.* So far as we are aware no experiments in which "artificial" food mixtures were introduced have ever been carried on successfully for an equal duration.

The most elaborate published nutrition experiments in respect to the variety of important details taken into consideration are those of Henriques† on white rats. He determined the changes in weight and the food-intake, as well as the complete daily nitrogen balance, in a large number of animals fed on artificially mixed diets. The isolated proteins used were casein, zein, and gliadin, with additions of sugar, lard, cellulose, and inorganic salts.‡ Only with casein and gliadin were the nitrogen balances favorable for the few days during which each trial was continued. This was true despite the gradual loss of body-weight noted in each case. It serves to emphasize what is frequently overlooked, viz., that a favorable nitrogen balance over a short period of time is in no sense an adequate index to a satisfactory nutritive condition. We have found that the body-weight of the rat is a more reliable guide to the real nutritive equilibrium of the animals than is the nitrogen balance.||

Valuable as the experiments of Henriques and Hansen have been for the purposes of orientation in a new field of research, the failures can not be adduced as proof of the inadequacy of the proteins selected, nor can the apparently successful results be accepted as conclusive. For the latter point, the duration of the experiments is far too short, as will be seen from the work of subsequent experimenters. The most serious criticism, perhaps, pertains to the food intake, which must have been within the lower limits of a *maintenance* ration for the animals which in many cases had not yet completed their growth. In respect to one conclusion the words of Henriques may be quoted:

Wir finden also, dass es eine Wesensverschiedenheit zwischen der Bedeutung des Zeins und der des Gliadins für den Stickstoffumsatz im Körper gibt; das Zein vermag kein Stickstoffgleichgewicht herzustellen, was dagegen das Gliadin vermag wenn es in reichlicher Menge gegeben wird. Der Grund dieser Verschiedenheit lässt sich natürlich nicht mit

*Falta and Noeggerath: Hofmeister's Beiträge zur chemischen Physiologie, 1905, VII, p. 320 (rats). Knapp: Zeitschrift für experimentelle Pathologie, 1908, v, p. 150, says: "Bekanntlich können z.B. Mäuse mit Milch monatelang ernährt werden und befinden sich wohl dabei." Socin: Zeitschrift für physiologische Chemie, 1891, xv, p. 93, fed mice 99 days on egg yolk alone.

†Henriques and Hansen: Zeitschrift für physiologische Chemie, 1904-5, XLIII, p. 417; 1908, LIV, p. 169; Henriques: *Ibid.*, 1909, LX, p. 105.

‡It should be noted that these included "Knochenmehl" (p. 419-420), which is not entirely free from nitrogenous matter. Was bone-ash intended?

||It may be worth while to point out here that we have found very considerable losses of nitrogen, especially in hot weather, when urine is collected by the method adopted by Henriques and by us, which will be described later. Such losses, amounting to 10 per cent and over, would obviously lead to the assumption of a greater retention of nitrogen than actually occurred and a consequent incorrect nitrogen balance.

Sicherheit angeben. Wir haben bereits angeführt, dass es beiden genannten Proteinen an Lysin abgeht. Dieser Mangel scheint also nicht von entschiedener Bedeutung zu sein. Dagegen scheint der Umstand, dass das Zein kein Tryptophan enthalt, eine grosse Rolle zu spielen. Ob das Nichtvorhandensein von Tryptophan, in Zein wirklich der Grund ist, weshalb bei Fütterung dieses Proteins kein Stickstoffgleichgewicht eintritt, muss sich übrigens durch eine Untersuchung entscheiden lassen, ob das Stickstoffgleichgewicht sich herstellen lässt, wenn das Futter Zein+Tryptophan enthält.*

The preceding quotation has suggested that the deficiency in a protein dietary need not be one of quantity; the structural character of the nitrogenous intake may determine its adequacy. Willcock and Hopkins† have approached the problem from this view-point. They fed mice on zein together with non-nitrogenous foods and compared their length of life with that of mice which received in addition some of the missing fragments of this "imperfect" protein, viz., tryptophane (and tyrosine for comparison). Zein was shown to be quite unable to take the place of a normal protein, like casein, in maintaining growth:

> The addition of the missing tryptophane group has no power to convert such loss (of weight) into equilibrium or gain—a fact possibly due to other deficiencies in the zein molecule, such as the absence of lysine. On the other hand, on the average, the loss of weight was slower with tryptophane than without it. But this result might well be expected, even if the tryptophane administered undergoes utilization without directly contributing to tissue formation or structural maintenance. If it serves as a basis for the elaboration of a substance absolutely necessary to life—something, for instance, of an importance equal to that of adrenaline—then, in starvation, or when it is absent from the diet, a supply is likely to be maintained from the tissue-proteids; the demand for it would become one of the factors determining tissue breakdown. In the case of young animals which directly benefit from the addition of a protein constituent, otherwise absent from their diet, to the extent of a well-nigh doubled life and marked improvement in general condition, but at the same time steadily lose, instead of gaining, weight, the utilization of the constituent would appear to be of some direct and specific nature. (p. 101.)

The suggestion of a possibility of the direct formation of essential hormones from amino-acid derivatives of proteins is timely. One can not draw any further conclusions regarding the value of the proteins (zein and casein) fed by Willcock and Hopkins, because in the absence of definite intake records, the question of a comparable and adequate supply of energy in the various cases remains undetermined. Special experiments showed that the prepared zein was "in no sense actively deleterious."

The same uncertainty regarding the real participation of inanition factors applies to the earlier widely quoted experiments of

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*Henriques: Zeitschrift für physiologische Chemie, 1909, LX, p. 117.
†Willcock and Hopkins: Journal of Physiology, 1906–7, XXXV, p. 88.

Lunin* on mice. Some of the animals were fed on casein as the sole protein. They survived only a month or less on the "artificial" diet, the author attributing the decline to defects in the intake of inorganic salts and other accessory foods.

Abderhalden and Rona† fed mice with casein, sugar, and sodium carbonate. The animals lived only 8 to 24 days on this obviously inadequate diet.

Falta and Noeggerath‡ recorded the changes of weight in rats kept on dietaries containing the nitrogen in the form of isolated (commercial) proteins: ovalbumin, casein, serum albumin, serum globulin, fibrin, and hæmoglobin. They fed no "roughage" in the form of cellulose. Neither these individual proteins nor mixtures of all were adequate to keep the animals alive longer than 94 days in the most favorable case. In most cases a gradual, steady decline was noted throughout the progress of the experiment. Death occurred when the animals had been reduced to two-thirds or three-fifths of their initial weight. The experiments clearly demonstrate the necessity of *prolonged* observation; for rats were maintained on the casein food mixture during several weeks without loss of weight, just as in Henriques' briefer trials of three to four weeks. Only later did the untoward effects manifest themselves. On milk, milk powder, or lean horse-meat rats could be kept six months or more.

The authors are properly guarded in their summary. They say:

Ob in der Periode des Gewichtabfalles in unseren Versuchen die Tiere genügend Nahrung aufgenommen haben, um ihr Kalorienbedürfnis zu decken, können wir nicht sicher angeben. Der Befund von Nahrungsresten im Digestionstractus der toten Tiere (Lunin) ist unseres Erachtens hierfür kein zwingender Beweis. Hier müssten genaue Stoffwechselversuche mit Berücksichtigung der Kraftbilanz einsetzen. Erst wenn der Einwand ungenügender Nahrungsaufnahme oder ungenügender Ausnützung, für welche beiden Momente man vielleicht die Einförmigkeit der Kost und den Mangel an Gewürzen verantwortlich machen könnte, beseitigt ist wären andere Gründe zu erörtern, wie z.B. der Mangel der nötigen chemischen Bausteine oder ein abweichendes chemisches Gefüge der eingeführten Nährstoffe. (p. 322.)

Utilizing the experience gained in the preceding research, Knapp‖ succeeded no better in maintaining his animals. He estimates the calorific needs of a 200 to 250 gram rat at 50 to 60 calories. The curves of change of body-weight and caloric intake go more or less parallel in Knapp's experiments and he notes that the specific role of individual nutrients can not be suitably ascertained until animals can be induced in some way to eat the requisite amount of calories

*Lunin: Zeitschrift für physiologische Chemie, 1881, v, p. 31.
†Abderhalden and Rona: Zeitschrift für physiologische Chemie, 1904, XLII, p. 528.
‡Falta and Noeggerath: Hofmeister's Beiträge zur chemischen Physiologie, 1905, VII, p. 314.
‖Knapp: Zeitschrift für experimentelle Pathologie, 1908, v, p. 147.

in the form of the "artificial" mixtures. The danger of drawing erroneous conclusions is attested by the fact that he was unable to maintain his rats upon a variety of food articles: dog biscuit, graham bread, rice, etc., which one would assume to be adequate as mixed food.

In explanation of his failures he says:

> Der Grund liegt hauptsächlich darin, dass die Thiere bei der reizlosen einförmigen Kost den Appetit verlieren, im geringeren Grade wohl auch darin, dass die Nahrung mit zunehmender Appetitlosigkeit im Darm auch weniger gut ausgenützt wird. (p. 168.)

It might have been expected that the difficulties here encountered could be obviated by the use of animals in which forced feeding could be satisfactorily instituted. C. Voit* kept a pigeon alive 124 days with peas by this method. Jacob† failed in repeated trials with pure food mixtures, and attributes his lack of success to the impossibility of adapting the physical texture of the introduced pure-food pellets to the requirements of the avian digestion apparatus, so that the pigeons died of inanition. He also attempted to advance beyond his predecessors in feeding "artificial" mixtures (with casein as the sole protein) to rats. He was scarcely more successful; the animals ate sparingly and he concludes that if it is possible to keep an animal alive 124 days, as he did, on a diet of the character noted, this must contain all the substances essential to life. The animals did not exhibit any gross pathological defects at autopsy, but all visible fat had disappeared. The next attempt, Jacob optimistically suggests, must be directed toward devising combinations which the animals will eat:

> So gelingt es vielleicht doch, eine Nahrung aus reinen Nahrstoffen ohne Genussmittel herzustellen, welche alle zur dauernden Erhaltung eines Tieres nötigen Stoffe im richtigen Mengenverhältnis enthält. (p. 60.)

McCollum‡ fed both young and full-grown rats on complex artificial mixtures, in which edestin, zein, and sometimes casein, were the sole sources of nitrogen. They are the most successful experiments yet reported as regards maintenance of body-weight or growth on a restricted quality of protein intake. The chief difficulty encountered was that of anorexia, which the author attempted to overcome by frequent changes in the combinations of food-stuffs used and by addition of flavors. Some of the trials extended over more than 100 days without death; but the rats failed to maintain their weights, even with the most persistent coaxing of the appetite. Data regarding the food intake are wanting, so that the inanition factor (due to deficient calories) can not be excluded.

*Voit: Zeitschrift für Biologie, 1866, II, p. 64.
†Jacob: Zeitschrift für Biologie, 1906, XLVIII, p. 19.
‡McCollum: American Journal of Physiology, 1909, XXV, p. 120.

More interesting even are his studies on the growth of young rats. They made considerable gains in weight in experiments with the proteins mentioned—without casein in one series and with it in the other—and extending over from 56 to 127 days. But the curves of growth do not approach those obtained for normal diet by Donaldson, to which we shall have occasion to refer again. McCollum concludes that "the palatability of the ration is the most important factor in animal nutrition" and "the failure of previous efforts to maintain animals on a mixture of relatively pure proximate constituents of our food-stuffs was due to the lack of palatability of such mixtures."

Finally reference must be made to the very successful attempts of Röhmann.* The details have not yet been published. Mice could be kept indefinitely on a mixture of casein, vitellin, egg albumin, and non-nitrogenous nutrients. They became mature and produced young which thrived. With only a single protein in the ration, a decline soon set in. If casein and egg albumin were used to replace each other the grown mice retained their weight, but the development of the younger ones was checked and they succumbed. Röhmann concluded from these facts that the different proteins possess a different significance for the nutrition and the development of young organisms.

Although none of our predecessors has returned a decisive answer to the fundamental question whether any single protein or combination of proteins is incapable of supplying all the essential chemical complexes which the body is unable to furnish to itself by direct synthesis, the pursuit of a solution by no means appears futile. None of the difficulties—actual or assumed—which have arisen appears experimentally insurmountable at present. The digestibility and utilization of the artificial rations has never been demonstrated to be abnormal or even unfavorable. The texture and inclusion of "roughage," such as is ordinarily a part of every mixed dietary in the guise of cellulose, can be experimentally adjusted, if indeed it is of any serious moment in controlling the mechanical functions of the alimentary tract.

Monotony of diet appears to have been overemphasized, if one may judge by the success with which milk or egg yolk have constituted the only food material for rats and mice. The failure common to all of the recorded experiments has been attributed to the difficulty of inducing animals to *eat sufficient food*. Strictly speaking, it has not been determined as yet whether the notable anorexia is the result of some unpalatable feature of the artificial food mixtures and thus the cause of the gradual inanition, or whether it is really a physiological sequence of an imperfect dietary.

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*Röhmann: Allgemeine Med. Central–Zeitung, 1903, No. 1; 1908, No. 9. Cf. Maly's Jahresbericht, 1903, xxxiii, p. 823; 1908, xxxviii, p. 659, for the same abstracts

The best hope of success—if such be possible—rests at present on the method of trial and error in which each variable is gradually eliminated by successive comparative experiments. This is the scheme which we have in large measure pursued. Our efforts have at first been directed toward devising a simple ration of isolated food components which should satisfy the numerous requirements set more adequately than any yet proposed. This established, substitutions could gradually be instituted in respect to the protein constituents. We learned before long that a diet which might be adequate for maintenance was by no means necessarily suited to the requirement of a growing animal. Hence our attention has become directed to some of the features of growth as well as those of the maintenance ration of the adult.

METHODS EMPLOYED.

The rats were kept in metabolism cages similar to that described by Henriques and Hansen.* A small door permits the introduction of food and water cups, such as are used in bird cages, through the side of the cage.

Figure A shows the essential features. Instead of weighing the food (which was always fed in the form of a homogeneous paste) in the food cups, we devised the following very simple plan to avoid frequent weighings. The food is introduced into a glass cylinder about 25 cm. in length and 3 cm. in diameter. A rubber stopper inserted into one end can be moved forward like a piston head and the food expelled from the other end of the cylinder into the food receptacle. The exit end of the cylinder is kept stopped when the food is not being expelled and the entire apparatus with its food content can be preserved in an ice-box for long periods without deterioration of the diet. The food eaten can thus be renewed at intervals and the quantity fed determined, when desired, by ascertaining the loss of weight of each food tube.

Figure B illustrates our feeding-tube device.

The urine and fæces were separately collected, the former in a receptacle containing boric acid and chloroform, and analyzed at intervals as indicated in the protocols. Control trials made by trickling known volumes of analyzed human urine over the cage bottom, and, after a suitable interval, washing with boric acid solution, collecting the urine, etc., just as in the rat experiments, indicated losses of 10 per cent or more. This must be borne in mind in considering our results and presumably those of other investigators.

We devoted great care to maintaining suitable environmental conditions (temperature, etc.), since the rats are sensitive to marked changes. With our diets they consumed large quantities of water.

*Henriques and Hansen: Zeitschrift für physiologische Chemie, 1904–5, XLIII, p. 418.

The success of the cage methods, as such, is shown by our ability to maintain animals in good health for very long periods in this way.

Confronted at the outset with the necessity of ascertaining whether the conditions selected—the caging, laboratory environment, consistency of the food and the mode of feeding, etc.—were
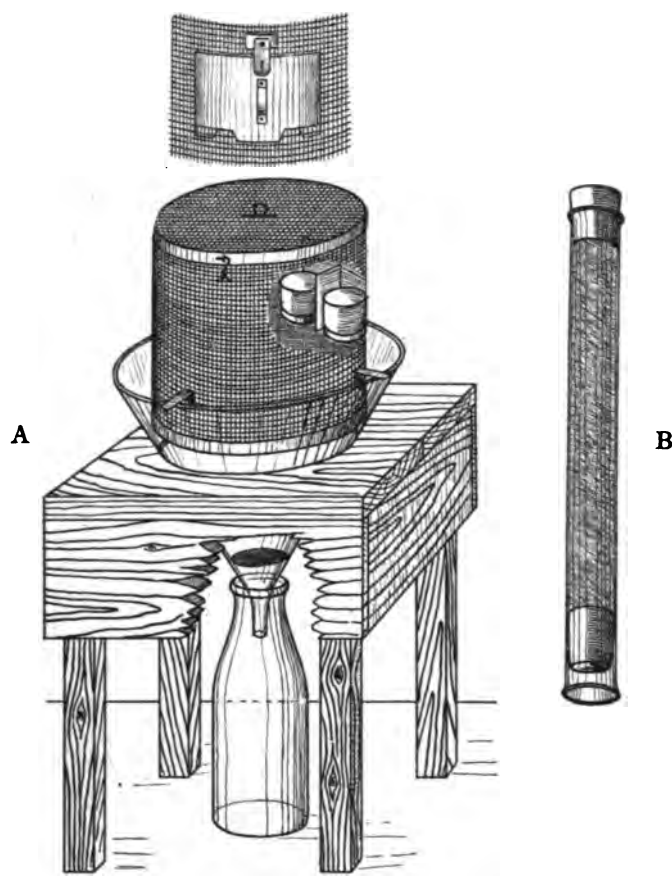
A. Sketch of cage used for feeding and collection of urine and fæces. Upper figure shows outer view of food-and-water-receptacle. (Reduced to one-twelfth natural size.)
B. Illustration of tube from which daily ration is discharged during each diet period. (Reduced to one-fourth natural size.)

endurable for the animals under any system of feeding, we undertook control trials with a mixed food in the form of dog biscuit and lard. This was prepared as follows:

The dry dog biscuits were ground to a moderately fine powder in a mill and usually 70 parts by weight were mixed with 30 parts of melted lard. The mixture when cooled was reduced to a homogeneous paste by passing several times through a meat-chopping machine. In this way the paste was forced through small holes in numerous filaments, to which a rotary motion was imparted, insuring a very

complete and rapid mixing of the ingredients of the paste. This method of mixing was used for all of the foods described in this paper.

A series of rats was fed with this food at the same time that other experimental diets were being investigated. In this way all the animals were exposed to the same indeterminable variables of climate and environment which might perchance have exerted an unsuspected deleterious influence and which would exhibit themselves in the control animals as well as those under special observa-
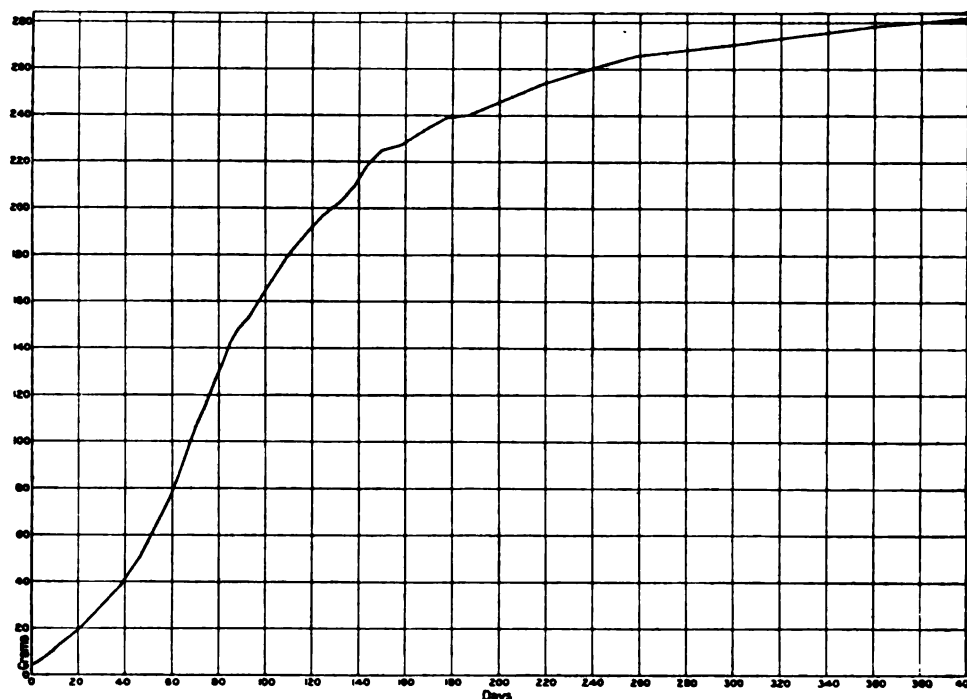
Chart I.—Average Normal Rate of Growth of Male White Rat, according to Donaldson.

tion. Like most of our trials during the first year of this work, they served chiefly for the purpose of orientation in respect to future procedure. It is scarcely necessary to record here the numerous individual experiments which resulted in a failure to maintain the rats in health and nutritive equilibrium. Failures, unless they are invariable in their occurrence, may well be due to accidents or incidents in no wise associated directly with the nutritive functions. Intercurrent parasitic diseases, incipient senility, hereditary defects, and other incidental features may be present or arise to interfere with the normal progress of an experiment. We have gradually learned to watch for such undesirable conditions and to exclude such animals as unsuitable for these studies, since proper allowance can

not be made for the perversions of function thereby introduced. For this reason we have been inclined to lay stress upon only those experiments which were either successful or which failed because of obvious causes.

In selecting criteria of adequate growth the painstaking statistical studies of Donaldson* on the adjustment of size to body-weight and age in the white rat have been of great help. After birth the young white rat depends upon the mother for sustenance for about 20 days. The span of life is about three years. Sexual maturity is reached in about 60 days. The first year of rat life corresponds, according to Donaldson, to the first thirty years of human life; and the growth curve for this period has been published by him. Some of the details are reproduced in Chart I.

The lack of appreciation of the salient features of these curves, representing graphically the gross normal increase in weight of white rats during the first third of their life, has led occasionally to conclusions which appear to us as quite erroneous. If, for example, a rat weighing 250 grams maintains its body-weight for several weeks without marked variations one may properly conclude that a normal nutritive equilibrium exists in such an animal; on the other hand a rat whose initial weight is 70 grams is in a period of most active growth. *Normal* nutrition for an animal in *this* phase calls for a measurable daily increment in weight and a gradual, yet detectable, increase in body-length. Within one month a 70-gram white rat ordinarily will double its weight when the diet is adequate. The illustrations cited suffice to indicate how different must be our criteria for the adolescent and the adult stages.

*Donaldson: A comparison of the white rat with man in respect to the growth of the entire body. Boas Memorial Volume, 1906.

EXPERIMENTAL PART.

CONTROL FEEDING.

A somewhat detailed protocol of the metabolism experiments on two of the "control" rats fed on dog biscuit and lard, as already mentioned, will serve as a typical description of the conduct of all our feeding trials. Rat XII and rat XIII were caged separately on August 9, 1909. Fresh food-paste (see page 13) was introduced daily into the food dishes in excess of the amount eaten, which was at first ascertained daily. The body-weights were at first determined every other day, as was the nitrogen of the excreta (urine and fæces). Subsequently it was found adequate to estimate the nitrogen balance in weekly periods. The data thus obtained are summarized

TABLE I.—SUMMARY OF DATA ON "CONTROL" RAT XII, FED ON DOG BISCUIT-LARD DIET FOR 147 DAYS.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Aug. 8....	143.5							
10....	150.0	9.5	0.143	0.107	0.027	0.134	81	+0.009
12....	155.0	9.2	0.139	0.103	0.029	0.132	79	+0.007
14....	157.7	8.7	0.132	0.096	0.037	0.133	72	−0.001
16....	156.5	7.8	0.124	0.098	0.030	0.128	76	−0.004
18....	162.0	9.3	0.149	0.106	0.012	0.118	92	+0.031
20....	165.5	9.1	0.144	0.106	0.031	0.137	78	+0.007
22....	165.0	8.1	0.129	0.088	0.021	0.109	84	+0.020
24....	164.1	7.0	0.112	0.080	0.022	0.102	80	+0.010
26....	165.5	6.6	0.103	0.075	0.022	0.097	79	+0.006
28....	165.2	6.7	0.105	0.073	0.021	0.094	80	+0.011
30....	162.6	5.8	0.091	0.069	0.027	0.096	70	−0.005
Sept. 1....	160.0	6.2	0.097	0.067	0.024	0.091	75	+0.006
3....	159.6	6.2	0.096	0.064	0.015	0.079	84	+0.017
5....	159.7	7.3	0.113	0.073	0.025	0.098	78	+0.015
7....	161.4	8.1	0.133	0.076	0.038	0.114	71	+0.019
9....	158.6	6.2	0.102	0.079	0.027	0.106	74	−0.004
11....	160.7	7.5	0.123	0.063	0.027	0.090	78	+0.033
13....	157.2	6.2	0.101	0.063	0.024	0.087	76	+0.014
15....	157.9	6.1	0.099	0.061	0.023	0.084	77	+0.015
17....	157.6	6.6	0.107	0.066	0.029	0.095	73	+0.012
19....	159.5	7.5	0.123	0.073	0.028	0.101	77	+0.022
26....	157.8	6.7	0.111	0.065	0.030	0.095	73	+0.016
Oct. 3....	154.8	5.5	0.091	0.080	0.022	0.102	76	−0.011
11....	158.5	6.4	0.094	0.067	0.018	0.085	81	+0.009
17....	150.0	4.5	0.074	0.082	0.023	0.105	69	−0.031
24....	147.5	5.1	0.084	0.067	0.015	0.082	82	+0.002
31....	142.2	4.8	0.080	0.052	0.020	0.072	75	+0.008
Nov. 7....	148.0	5.4	0.090	0.055	0.016	0.071	82	+0.019
14....	141.1	3.9	0.065	0.050	0.014	0.064	78	+0.001
21....	142.7	4.6	0.077	0.057	0.015	0.072	81	+0.005
28....	143.7	4.7	0.079	0.049	0.020	0.069	75	+0.010
Dec. 5....	141.3	4.3	0.071	0.057	0.015	0.072	79	−0.001
12....	147.3	5.0	0.083	0.058	0.014	0.072	83	+0.011
19....	152.2	5.4	0.090	0.058	0.015	0.073	83	+0.017
26....	150.4	5.1	0.084	0.063	0.016	0.079	81	+0.005
1910.								
Jan. 2....	151.7	4.8	0.079	0.057	0.017	0.074	78	+0.005

in tables and also reproduced in graphic form. This experiment in common with many others was concluded after 153 days on January 10, 1910, by a fire which destroyed all of our experimental animals.

Tables I and II give the data for the "control" rats XII and XIII, which had been obtained up to January 3, 1910, a period of 147 days, at the end of which time both rats showed a distinct gain in weight and a considerable gain of nitrogen:

TABLE II.—SUMMARY OF DATA ON "CONTROL" RAT XIII, FED ON DOG BISCUIT-LARD DIET FOR 147 DAYS.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Aug. 8....	255.5	....						
10....	266.0	12.4	0.187	0.145	0.039	0.184	79	+0.003
12....	268.8	11.1	0.168	0.197	0.041	0.238	76	-0.070
14....	275.7	12.7	0.191	0.126	0.038	0.164	80	+0.027
16....	280.0	12.1	0.192	0.171	0.039	0.210	80	-0.018
18....	287.5	13.4	0.214	0.133	0.044	0.177	79	+0.037
20....	296.1	13.2	0.210	0.177	0.041	0.218	80	-0.008
22....	303.5	13.6	0.216	0.146	0.038	0.184	82	+0.032
24....	307.0	13.8	0.219	0.150	0.047	0.197	79	+0.022
26....	317.0	13.6	0.213	0.149	0.044	0.193	79	+0.020
28....	325.0	13.8	0.216	0.152	0.042	0.194	81	+0.022
30....	329.5	13.7	0.214	0.144	0.040	0.184	81	+0.030
Sept. 1....	333.1	13.6	0.212	0.141	0.046	0.187	78	+0.025
3....	328.2	12.3	0.192	0.134	0.034	0.168	82	+0.024
5....	327.0	13.3	0.207	0.139	0.043	0.182	79	+0.025
7....	327.2	13.0	0.212	0.141	0.043	0.184	80	+0.028
9....	325.8	12.5	0.203	0.146	0.040	0.186	80	+0.017
11....	329.0	11.9	0.194	0.129	0.036	0.165	81	+0.029
13....	328.1	11.9	0.194	0.140	0.036	0.176	81	+0.018
15....	330.6	12.7	0.207	0.138	0.038	0.176	82	+0.031
17....	329.8	12.4	0.202	0.140	0.038	0.178	81	+0.024
19....	331.9	12.1	0.197	0.147	0.030	0.177	85	+0.020
26....	319.7	11.2	0.187	0.127	0.038	0.165	80	+0.022
Oct. 3....	322.8	12.5	0.207	0.159	0.034	0.193	84	+0.014
11....	334.7	13.9	0.198	0.137	0.038	0.175	81	+0.023
17....	335.8	12.2	0.200	0.171	0.042	0.213	79	-0.013
24....	334.5	10.5	0.175	0.126	0.031	0.157	82	+0.018
31....	330.5	10.3	0.171	0.142	0.030	0.172	82	-0.001
Nov. 7....	332.0	10.9	0.183	0.131	0.033	0.164	82	+0.019
14....	334.8	10.8	0.181	0.126	0.035	0.161	81	+0.020
21....	328.8	9.7	0.162	0.119	0.031	0.150	81	+0.012
28....	333.4	9.8	0.163	0.110	0.028	0.138	83	+0.025
Dec. 5....	327.3	8.4	0.138	0.114	0.025	0.139	82	-0.001
12....	323.8	9.3	0.154	0.123	0.027	0.150	82	+0.004
19....	321.6	9.3	0.153	0.105	0.028	0.133	82	+0.020
26....	308.6	7.9	0.131	0.100	0.023	0.123	82	+0.008
1910.								
Jan. 2....	307.5	8.3	0.138	0.115	0.022	0.137	84	+0.001

These and other analytical data have been introduced in this paper in part reproduced in graphic form. In all of the charts the abscissa units represent days, and the ordinate units food (broken line) or body-weight (solid line). The food-intake curve is plotted from the total amount eaten per week. The average daily nitrogen balance is indicated as above (+) or below (—) the heavy line (o).
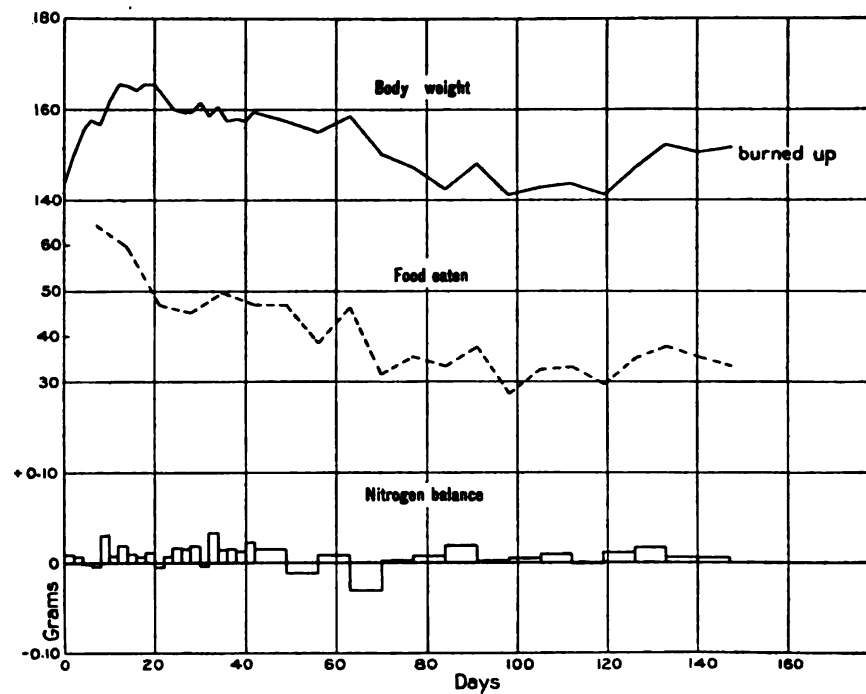
CHART II.—"Control" Rat xii fed on Dog Biscuit-Lard Diet for 147 days.
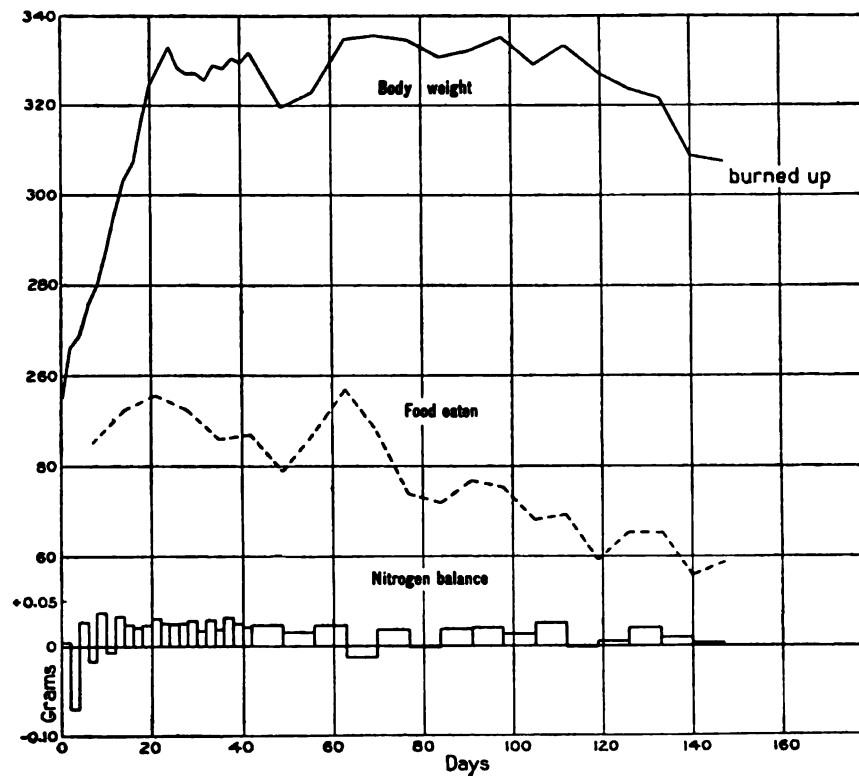
CHART III.—"Control" Rat xiii fed on Dog Biscuit-Lard Diet for 147 days.

DISCUSSION.

It will be noted that Rats XII and XIII, representing different ages, if we judge from the initial weights, were maintained in nutritive equilibrium without loss of body-weight during the period of 147 days—a not inconsiderable fraction of the life span of these animals. There is, however, a gradual decline in the amount of food which is eaten toward the end of the experiment, the quantity in the case of XII approaching limits which must have necessitated some demand upon the fat supply earlier accumulated. The utilization of the protein continued satisfactory, thus evincing unimpaired digestive powers   It is far from likely that the ration used, with its large preponderance of energy in the form of fat, is an ideal one. The facts recorded, however, exclude the probability that monotony of diet is an insurmountable obstacle to nutritive success.*

As to the possibility of prolonged feeding on a uniform unchanged diet, two illustrations are appended of experiments on rats 14 and 18 fed with a mixture of ground hempseed, starch, lard, and salts. These rats were first fed with a mixture of dog biscuit and lard for several weeks and then on the hempseed mixture.   The composition of the food given during the different periods is shown in table III.

TABLE III.—COMPOSITION OF THE FOOD IN PERCENTAGES.

	Dog-biscuit.	Lard.	Nitrogen.	Hemp-seed.	Starch.	Lard.	Sodium chloride.	Salt mixture I.†	Nitrogen.
Rat 14.									
Period 1....	58	42	1.6						
Period 2....	70	30	1.9						
Period 3....				46	42	10	2		2.27
Period 4....				46	42	10		2	2.40
Period 5....				50	38	10		2	2.32
Rat 18.									
Period 1....	58	42	1.6						
Period 2....	70	30	1.9						
Period 3....				46	42	10	2		2.27
Period 4....				46	42	10		2	2.39
Period 5....				50	38	10		2	2.45

The figures for nitrogen are averages of the different batches of food which were made up from time to time.   The hempseed meal was freed from the greater part of the hulls by sifting, but the different lots contained different proportions which escaped separation; hence the actual nitrogen content of the individual batches of food varied somewhat.   The figures given in the protocols and representing daily averages are based on the actual quantity of nitrogen fed, not on the averages given in table III.

*Among the many often unapparent difficulties which beset such experiments, the frequent occurrence of intestinal parasites and the susceptibility of the animals o digestive disturbances are to be noted.

†The salt mixture 1, which contained organic and inorganic salts of the necessary bases and acids, is described on page 32.

Rat 14 lived 200 days without marked change in weight (losing less than 10 per cent); rat 18 (still on the same diet after 322 days at the time of writing) weighs very nearly as much as at the beginning of the hempseed feeding.

TABLE IV.—SUMMARY OF DATA ON RAT 14 FED ON HEMPSEED-STARCH-LARD DIET FOR 207 DAYS.— DAILY AVERAGES.

PERIOD I.

| Date of experiment. | Body-weight. | Intake. | | Nitrogen output. | | | N-utilization. | N-balance. |
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Jan. 24....	284.0							
31....	274.2	8.5	0.134	0.123	0.029	0.152	78	—0.018
Feb. 7....	268.3	8.2	0.133	0.133	0.023	0.156	83	—0.023

PERIOD 2.

Feb. 14....	262.5	8.7	0.168	0.137	0.032	0.169	81	—0.001
21....	255.4	7.4	0.143	0.147	0.027	0.174	81	—0.031
28....	257.0	9.3	0.178	0.145	0.032	0.177	82	+0.001
Mar. 7....	259.6	8.9	0.168	0.136	0.028	0.164	83	+0.004

PERIOD 3.

Mar. 14....	208.0	.6	0.013	0.115	0.011	0.126	15	—0.113
21....	212.2	5.4	0.123	0.131	0.016	0.147	87	—0.024

PERIOD 4.

Mar. 28....	234.2	9.7	0.231	0.144	0.044	0.188	81	+0.043
Apr. 4....	252.0	11.2	0.270	0.157	0.056	0.213	79	+0.057
18....	237.7	8.1	0.193	0.162	0.037	0.199	81	—0.006
May 2....	244.5	8.3	0.199	0.161	0.039	0.200	80	—0.001
16....	260.3	9.4	0.288	0.168	0.056	0.224	75	+0.004
30....	250.2	7.3	0.176	0.143	0.027	0.170	85	+0.006
June 6....	254.0	9.9	0.234	0.158	0.046	0.204	80	+0.030
20....	242.0	8.3	0.194	0.150	0.044	0.194	77	0.000

PERIOD 5.

June 27....	251.8	8.5	0.205	0.142	0.039	0.181	81	+0.024
July 4....	248.0	8.1	0.200	0.155	0.026	0.181	87	+0.019
11....	247.4	8.4	0.208	0.156	0.043	0.199	79	+0.009
18....	251.5	8.7	0.210	0.127	0.045	0.172	79	+0.038
25....	253.0	8.9	0.213	0.148	0.040	0.188	81	+0.025
Aug. 1....	261.8	10.5	0.252	0.141	0.069	0.210	73	+0.042
8....	264.8	9.2	0.232	0.103	0.018	0.121	92	+0.111
15....	262.2	12.2	0.249	0.134	0.064	0.198	74	+0.051
22....	266.6	12.5	0.253	0.108	0.076	0.184	70	+0.069
29....	252.2	10.9	0.221	0.105	0.069	0.174	69	+0.047
Sept. 5....	249.5	11.8	0.262	0.141	0.077	0.218	71	+0.044
12....	241.5	9.5	0.219	0.174	0.044	0.218	80	+0.001
19....	245.0	13.5	0.314	0.215	0.101	0.316	68	—0.002
26....	237.8	10.1	0.235	0.201	0.051	0.252	78	—0.017
30....	180.2							
Dead.								
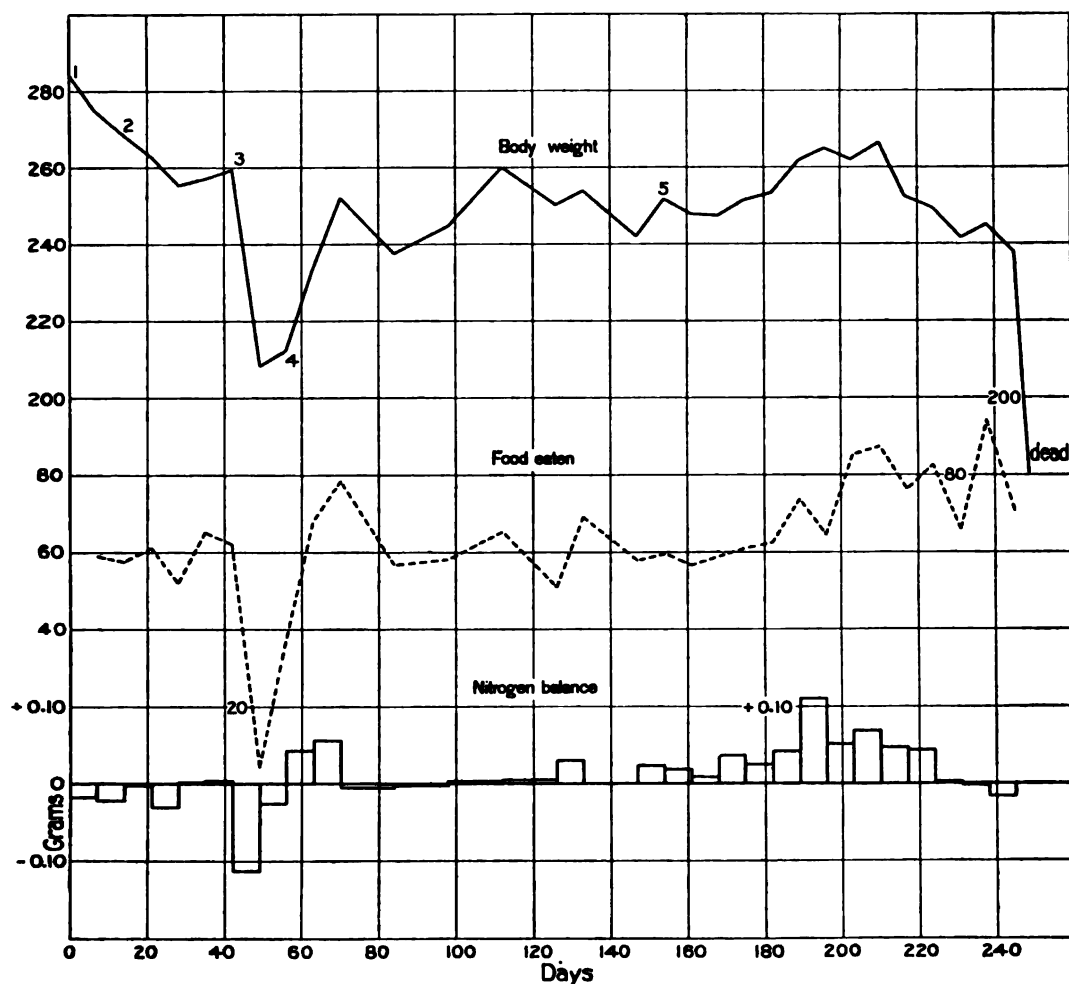
CHART IV.—Rat 14 fed on Hempseed-Lard Diet for 207 days. Numbers on body-weight
line indicate time at which each period began.

TABLE V.—SUMMARY OF DATA ON RAT 18 FED ON HEMPSEED-STARCH-LARD DIET
FOR 322 DAYS.—DAILY AVERAGES.

PERIOD 1.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. cl.	gm.
Jan. 24....	268.3	......	......	......	......	......	......	......
31....	248.7	6.2	0.099	0.121	0.024	0.145	76	−0.046
Feb. 7....	233.5	4.9	0.078	0.095	0.015	0.110	81	−0.032

PERIOD 2.

Feb. 14....	237.0	8.5	0.163	0.142	0.027	0.169	83	−0.006
21....	248.0	9.2	0.177	0.145	0.027	0.172	85	+0.005
28....	251.8	8.9	0.171	0.111	0.035	0.146	80	+0.025

TABLE V.—SUMMARY OF DATA ON RAT 18 FED ON HEMPSEED-STARCH-LARD DIET
FOR 322 DAYS.—DAILY AVERAGES—CONTINUED.

PERIOD 3.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Faeces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Mar. 7....	236.0	3.2	0.072	0.099	0.018	0.117	75	—0.045
14....	200.0	3.5	0.080	0.127	0.027	0.154	66	—0.074
21....	194.7	6.2	0.140	0.104	0.034	0.138	76	+0.002
28....	182.0	3.5	0.079	0.117	0.042	0.159	47	—0.080

PERIOD 4.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Faeces.	Total.	N-utilization.	N-balance.
Apr. 4....	168.2	4.2	0.098	0.131	0.018	0.149	82	—0.051
18....	159.0	5.4	0.129	0.135	0.028	0.163	78	—0.034
May 2....	175.5	6.7	0.161	0.114	0.026	0.140	84	+0.021
16....	216.0	11.8	0.287	0.118	0.060	0.178	79	+0.109
30....	230.0	7.7	0.187	0.107	0.032	0.139	83	+0.048
June 6....	229.0	8.5	0.205	0.102	0.041	0.143	80	+0.062
20....	242.0	8.2	0.195	0.109	0.046	0.155	76	+0.040
27....	235.0	5.8	0.135	0.104	0.027	0.131	80	+0.004
July 4....	235.5	8.0	0.188	0.127	0.036	0.163	81	+0.025
11....	243.8	9.3	0.230	0.138	0.041	0.179	82	+0.051

PERIOD 5.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Faeces.	Total.	N-utilization.	N-balance.
July 18....	243.1	7.2	0.177	0.119	0.039	0.158	78	+0.019
25....	242.5	7.6	0.183	0.139	0.035	0.174	81	+0.009
Aug. 1....	240.0	8.4	0.201	0.142	0.043	0.185	79	+0.016
8....	255.0	9.3	0.223	0.144	0.044	0.188	80	+0.035
15....	261.7	12.7	0.264	0.138	0.086	0.224	67	+0.040
22....	257.3	11.8	0.240	0.131	0.072	0.203	70	+0.037
29....	261.2	13.9	0.288	0.117	0.096	0.213	67	+0.075
Sept. 5....	256.0	10.5	0.240	0.137	0.086	0.223	64	+0.017
12....	239.0	8.8	0.203	0.189	0.044	0.233	78	—0.030
19....	234.0	11.8	0.275	0.193	0.085	0.278	69	—0.003
26....	215.8	7.3	0.171	0.191	0.037	0.228	78	—0.057
Oct. 3....	220.5	11.0	0.257	0.185	0.045	0.230	82	+0.027
10....	231.5	11.5	0.301	0.216	0.041	0.257	86	+0.044
17....	228.7	10.5	0.275	0.200	0.068	0.268	75	+0.007
24....	225.0	8.7	0.227	0.187	0.060	0.247	74	—0.020
31....	230.8	9.6	0.255	0.171	0.055	0.226	78	+0.029
Nov. 7....	230.0	10.2	0.281	0.185	0.076	0.261	73	+0.020
14....	227.0	7.6	0.209	0.173	0.048	0.221	77	—0.012
21....	218.7	8.3	0.229	0.196	0.042	0.238	82	—0.009
28....	222.5	8.5	0.233	0.164	0.037	0.201	84	+0.032
Dec. 5....	233.2	10.1	0.276	0.196	0.048	0.244	83	+0.032
12....	220.5	9.2	0.253	0.204	0.058	0.262	77	—0.009
19....	233.3	10.6	0.292	0.196	0.058	0.254	80	+0.038
26....	....	9.0	0.246	0.191	0.055	0.246	78	0.000
1911.								
Jan. 2....	239.0	9.7	0.253	0.174	0.058	0.232	77	+0.021
9....	232.7	6.6	0.164	0.143	0.024	0.167	85	—0.003
16....	239.8	7.7	0.191	0.148	0.024	0.172	87	+0.019
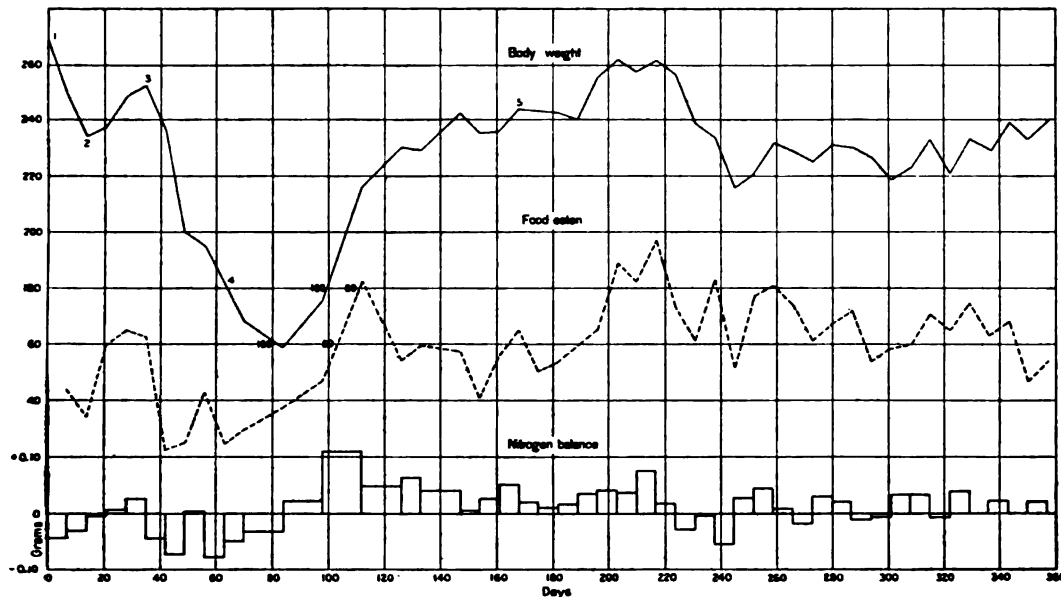
CHART V.—Rat 18 fed on Hempseed-Lard Diet for 322 days. Numbers on body-weight line indicate time at which each period began.

Other trials with the same diets frequently led to a decline in weight and a loss of body protein. In nearly all of these cases the insufficient food-intake was adequate to explain the incipient symptoms of inanition. Our numerous attempts to vary the flavor of the food and thus increase its palatability have been without striking success. Under exactly similar conditions of diet and environment different rats may continue to exhibit markedly unlike appetite for the same food. It seems best in the present stage of our knowledge to exclude from the diet experiments all animals which exhibit what seems like a temperamental anorexia. Protocols from some of these experiments are recorded here for comparison.

Rats xxviii and xxix were fed throughout the entire period on the dog biscuit-lard mixture with the results shown in tables VI and VII.

TABLE VI.—SUMMARY OF DATA ON RAT XXVIII FED ON DOG BISCUIT-LARD DIET FOR 105 DAYS.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Sept. 19....	176.0							
21....	170.4	7.8	0.126	0.122	0.043	0.165	66	—0.039
23....	171.8	7.1	0.114	0.107	0.036	0.143	68	—0.029
25....	170.5	7.5	0.125	0.096	0.032	0.128	74	—0.003
30....	155.1	5.6	0.093	0.106	0.020	0.126	78	—0.033
Oct. 3....	152.8	5.8	0.096	0.096	0.026	0.122	73	—0.026
10....	152.5	5.9	0.095	0.082	0.019	0.101	80	—0.006
17....	147.5	5.1	0.083	0.075	0.018	0.093	78	—0.010
24....	148.5	6.9	0.114	0.080	0.022	0.102	81	+0.012
31....	141.3	4.8	0.080	0.067	0.012	0.079	85	+0.001
Nov. 7....	145.0	5.7	0.095	0.066	0.012	0.078	87	+0.017
14....	143.8	6.1	0.106	0.072	0.018	0.090	83	+0.016
21....	143.4	5.4	0.099	0.070	0.016	0.086	84	+0.013
28....	135.5	5.0	0.091	0.083	0.016	0.099	82	—0.008
Dec. 5....	134.5	5.3	0.097	0.080	0.017	0.097	82	0.000
12....	131.5	5.8	0.107	0.090	0.021	0.111	80	—0.004
19....	126.6	5.2	0.096	0.078	0.019	0.097	80	—0.001
26....	119.4	4.8	0.080	0.075	0.016	0.091	80	—0.011
1910.								
Jan. 2....	116.9	5.6	0.093	0.087	0.023	0.110	75	—0017

TABLE VII.—SUMMARY OF DATA ON RAT XXIX FED ON DOG BISCUIT-LARD DIET FOR 103 DAYS.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Sept. 19....	175.0							
21....	170.2	8.6	0.138	0.138	0.038	0.176	72	—0.038
23....	174.2	8.8	0.141	0.127	0.035	0.162	75	—0.021
25....		8.3	0.137	0.103	0.032	0.135	77	+0.002
30....	163.3	6.6	0.107	0.107	0.025	0.132	77	—0.025
Oct. 3....	164.4	8.2	0.136	0.106	0.028	0.134	79	+0.002
10....	162.4	7.2	0.119	0.094	0.028	0.122	76	—0.003
17....	156.4	6.4	0.105	0.083	0.026	0.109	75	—0.004
24....	155.0	7.7	0.128	0.079	0.026	0.105	80	+0.023
31....	151.5	6.6	0.110	0.075	0.021	0.096	81	+0.014
Nov. 7....	150.6	6.9	0.116	0.079	0.025	0.104	78	+0.012
14....	151.0	6.2	0.111	0.075	0.018	0.093	84	+0.018
21....	153.4	6.9	0.125	0.077	0.023	0.100	82	+0.025
28....	150.3	7.8	0.142	0.076	0.023	0.099	84	+0.043
Dec. 5....	146.8	6.4	0.117	0.082	0.027	0.109	77	+0.008
12....	142.2	6.0	0.110	0.086	0.025	0.111	77	—0.011
19....	124.7	3.2	0.058	0.069	0.014	0.083	76	—0.025
26....	111.9	3.7	0.062	0.078	0.015	0.093	76	—0.031
31....	95.5	3.5	0.057	0.092	0.026	0.118	54	—0.061
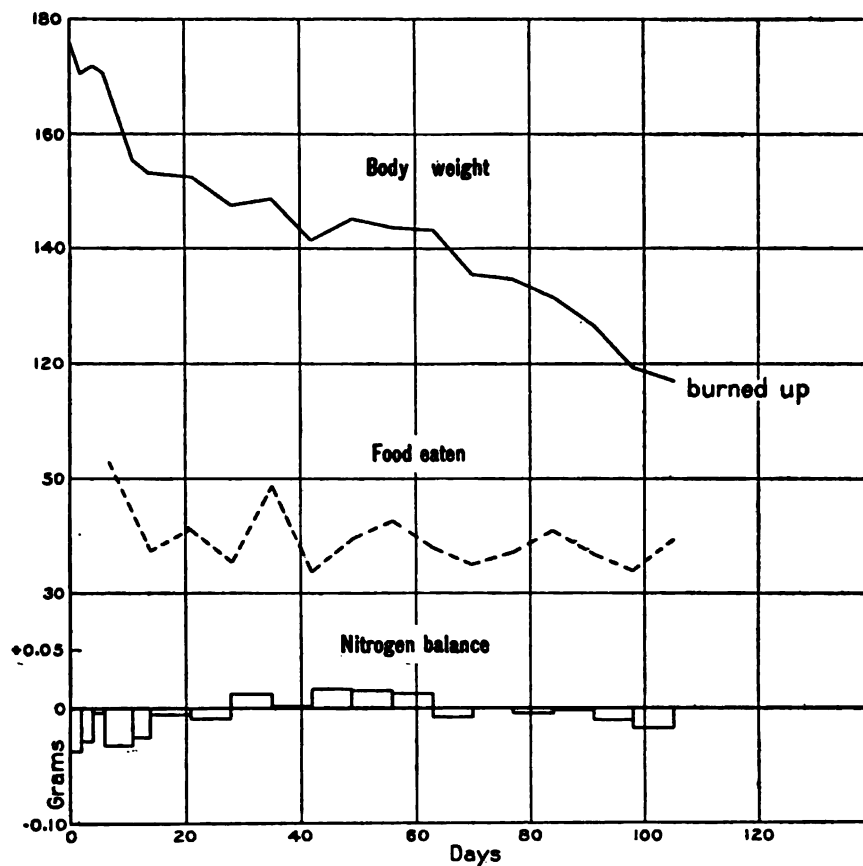
CHART VI.—Rat xxviii fed on Dog Biscuit-Lard Diet for 105 days.

TABLE VIII.—COMPOSITION OF THE FOOD IN PERCENTAGES.

	Dog biscuit.	Lard.	Nitrogen.	Trumilk.*	Starch (arrowroot).	Lard.	Salt mixture I.	Nitrogen.
RAT 10.								
Period 1.....	58.0	42.0	1.58	.....	.....	.....	.....	.....
Period 2.....	70.0	30.0	1.93	.....	.....	.....	.....	.....
Period 3.....	.....	.....	.....	54.0*†	16.0	30.0	.....	2.51
Period 4.....	.....	.....	.....	52.0*†	18.0	30.0	.....	2.87
Period 5.....	.....	.....	.....	42.0*†	24.0	34.0	.....	2.31
RAT 11.								
Period 1.....	58.0	42.0	1.58	.....	.....	.....	.....	.....
Period 2.....	70.0	30.0	1.93	.....	.....	.....	.....	.....
Period 3.....	.....	.....	.....	60.0	16.7	23.3	.....	2.53
RAT 12.								
Period 1.....	58.0	42.0	1.58	.....	.....	.....	.....	.....
Period 2.....	70.0	30.0	1.93	.....	.....	.....	.....	.....
Period 3.....	.....	.....	.....	60.0	16.7	23.3	.....	2.53
Period 4.....	.....	.....	.....	60.0	15.7	23.3	1.0	2.47

*"Trumilk" is a commercial milk powder.
†This was extracted in the laboratory once with 95 per cent alcohol, once with absolute alcohol, and four times with ether.
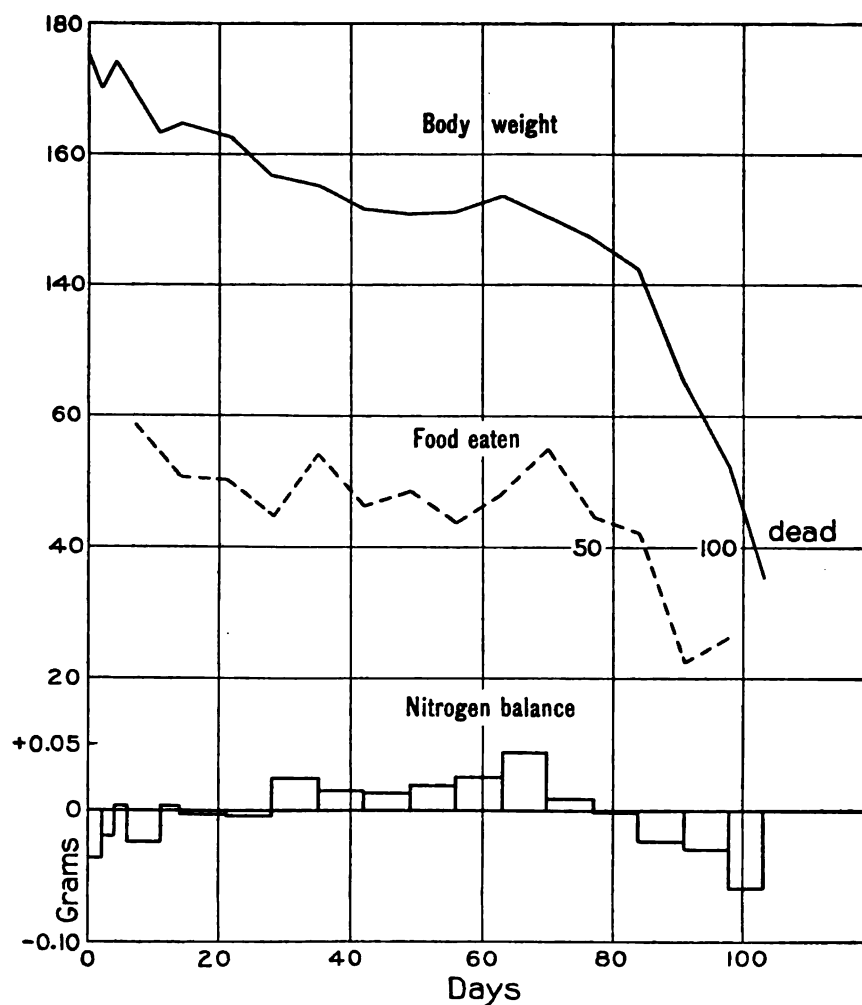
CHART VII.—Rat xxix fed on Dog Biscuit-Lard Diet for 103 days.

Rats 10, 11, and 12 were first fed on the dog biscuit-lard mixture and later on one containing desiccated milk. The composition of their food is shown in table VIII.

TABLE IX.—SUMMARY OF DATA ON RAT 10 FED ON DOG BISCUIT-LARD DIET FOR 98 DAYS AND THEN ON MILK POWDER-STARCH-LARD DIET FOR 84 DAYS.—DAILY AVERAGES.

PERIOD 1.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Jan. 24....	237.6							
31....	216.3	4.8	0.075	0.102	0.015	0.117	80	−0.042
Feb. 7....	210.0	5.7	0.090	0.107	0.014	0.121	84	−0.031

PERIOD 2.

Feb. 14....	208.0	7.9	0.151	0.127	0.029	0.156	81	−0.005
21....	211.3	8.1	0.155	0.129	0.027	0.156	83	−0.001
28....	212.7	6.9	0.132	0.105	0.022	0.127	83	+0.005
Mar. 7....	208.7	6.0	0.115	0.107	0.018	0.125	84	−0.010
14....	200.0	5.1	0.096	0.104	0.016	0.120	83	−0.024
21....	193.7	5.0	0.096	0.104	0.016	0.120	83	−0.024
Apr. 4....	186.5	5.7	0.112	0.098	0.018	0.116	84	−0.004
18....	177.5	5.6	0.106	0.103	0.014	0.117	87	−0.011
May 2....	182.8	6.4	0.120	0.101	0.018	0.119	85	+0.001

PERIOD 3.

May 9....	189.7	5.8	0.145	0.116	0.013	0.129	91	+0.016
16....	196.5	6.3	0.159	0.084	0.023	0.107	86	+0.052
23....	191.5	5.5	0.138	0.118	0.015	0.133	89	+0.005

PERIOD 4.

May 30....	185.0	5.1	0.134	0.134	0.014	0.148	90	−0.014
June 6....	175.5	5.9	0.169	0.169	0.019	0.188	89	−0.019
13....	172.1	6.4	0.183	0.167	0.013	0.180	93	+0.003
20....	176.2	4.6	0.132	0.146	0.011	0.157	92	−0.025

PERIOD 5.

June 27....	165.5	4.5	0.104	0.113	0.018	0.131	83	−0.027
July 4....	163.7	4.9	0.114	0.119	0.014	0.133	88	−0.019
11....	149.6	4.5	0.103	0.117	0.014	0.131	86	−0.028
18....	142.5	4.1	0.095	0.108	0.017	0.125	82	−0.030
25....	134.3	4.4	0.104	0.131	0.022	0.153	79	−0.049
Chloroformed								

TABLE X.—SUMMARY OF DATA ON RAT 11 FED ON DOG BISCUIT-LARD DIET FOR 84 DAYS AND THEN ON MILK POWDER-STARCH-LARD DIET FOR 94 DAYS.—DAILY AVERAGES.

PERIOD 1.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Jan. 24....	224.3							
31....	213.7	6.4	0.101	0.107	0.018	0.125	82	—0.024
Feb. 7....	208.8	7.3	0.116	0.116	0.020	0.136	83	—0.020

PERIOD 2.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Fæces.	Total.	N-utilization.	N-balance.
1910.								
Feb. 14....	196.7	6.3	0.120	0.115	0.020	0.135	83	—0.015
21....	202.5	7.4	0.142	0.126	0.018	0.144	87	—0.002
28....	195.0	6.4	0.123	0.120	0.023	0.143	81	—0.020
Mar. 7....	198.0	6.9	0.131	0.110	0.021	0.131	84	0.000
14....	187.3	5.3	0.100	0.102	0.015	0.117	85	—0.017
21....	190.1	5.1	0.100	0.102	0.018	0.120	82	—0.020
Apr. 4....	165.0	6.3	0.123	0.102	0.019	0.121	85	+0.002
18....	170.2	6.6	0.129	0.111	0.020	0.131	84	—0.002

PERIOD 3.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Fæces.	Total.	N-utilization.	N-balance.
1910.								
Apr. 25....	188.0	7.1	0.179	0.097	0.010	0.107	94	+0.072
May 2....	194.6	7.0	0.176	0.120	0.023	0.143	87	+0.033
9....	193.5	7.3	0.182	0.132	0.030	0.162	84	+0.020
16....	194.3	6.8	0.170	0.137	0.021	0.158	88	+0.012
23....	200.0	6.9	0.174	0.130	0.021	0.151	88	+0.023
30....	192.2	5.1	0.129	0.118	0.013	0.131	90	—0.002
June 6....	183.5	5.9	0.151	0.147	0.021	0.168	86	—0.017
13....	172.1	4.1	0.105	0.159	0.019	0.178	82	—0.073
20....	191.5	7.3	0.183	0.148	0.020	0.168	89	+0.015
27....	190.2	5.8	0.146	0.102	0.022	0.124	85	+0.022
July 4....	188.5	6.1	0.153	0.127	0.024	0.151	84	+0.002
11....	187.0	5.8	0.145	0.141	0.029	0.170	80	—0.025
18....	183.7	6.2	0.155	0.123	0.028	0.151	82	+0.004
21....	154.5							
Dead								

TABLE XI.—SUMMARY OF DATA ON RAT 12 FED ON DOG BISCUIT-LARD DIET FOR 84 DAYS AND THEN ON MILK POWDER-STARCH-LARD DIET FOR 113 DAYS.—DAILY AVERAGES.

PERIOD 1.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Jan. 24....	231.7							
31....	212.0	5.7	0.091	0.096	0.021	0.117	77	—0.026
Feb. 7....	196.3	5.3	0.085	0.104	0.016	0.120	81	—0.035

PERIOD 2.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Fæces.	Total.	N-utilization.	N-balance.
1910.								
Feb. 14....	192.2	6.1	0.118	0.116	0.019	0.135	84	—0.017
21....	187.6	6.6	0.127	0.134	0.025	0.159	80	—0.032
28....	182.5	6.1	0.118	0.124	0.019	0.143	84	—0.025
Mar. 7....	181.3	5.5	0.104	0.114	0.012	0.126	88	—0.022
14....	182.2	7.1	0.134	0.117	0.020	0.137	85	—0.003
21....	184.6	7.3	0.141	0.108	0.015	0.123	89	+0.018
Apr. 4....	176.2	5.8	0.113	0.109	0.021	0.130	81	—0.017
18....	171.2	6.0	0.118	0.109	0.018	0.127	85	—0.009

PERIOD 3.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Fæces.	Total.	N-utilization.	N-balance.
1910.								
Apr. 25....	188.7	6.3	0.159	0.091	0.014	0.105	91	+0.054
May 2....	191.7	6.3	0.158	0.107	0.018	0.125	89	+0.033
9....	198.5	7.2	0.180	0.126	0.021	0.147	88	+0.033
16....	196.7	7.1	0.178	0.126	0.028	0.154	84	+0.024
23....	196.4	6.0	0.151	0.117	0.021	0.138	86	+0.013
30....	196.6	5.6	0.142	0.109	0.025	0.134	82	+0.008
June 6....	181.4	5.7	0.146	0.141	0.027	0.168	82	—0.022
13....	176.3	5.3	0.135	0.132	0.014	0.146	90	—0.011
20....	175.0	4.7	0.118	0.131	0.013	0.144	89	—0.026
27....	173.3	4.5	0.112	0.099	0.010	0.109	91	+0.003
July 4....	165.6	4.8	0.122	0.125	0.018	0.143	85	—0.021
11....	162.5	5.0	0.126	0.138	0.012	0.150	90	—0.024
18....	155.0	4.6	0.115	0.119	0.014	0.133	88	—0.018
25....	143.5	4.1	0.103	0.163	0.009	0.172	91	—0.069

PERIOD 4.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Fæces.	Total.	N-utilization.	N-balance.
1910.								
Aug. 1....	137.0	4.6	0.114	0.104	0.017	0.121	85	—0.007
8....	115.5	3.7	0.091	0.129	0.015	0.144	84	—0.053
9....	110.5							
Dead								
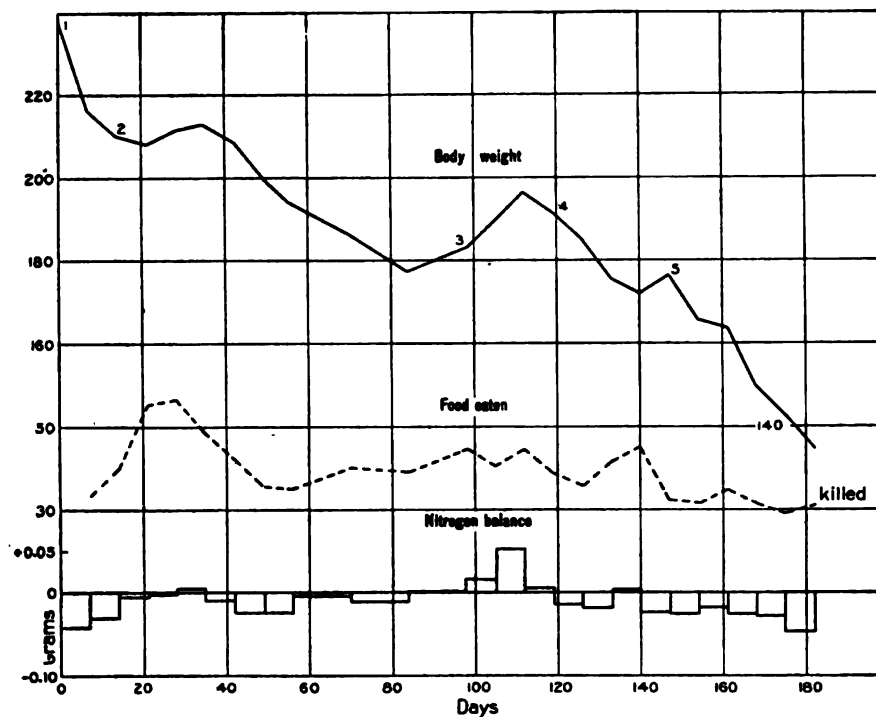
CHART VIII.—Rat 10 fed on Dog Biscuit-Lard Diet for 98 days and then on Milk powder-Starch-Lard Diet for 84 days. Numbers on Body-weight line indicate time at which each period began.
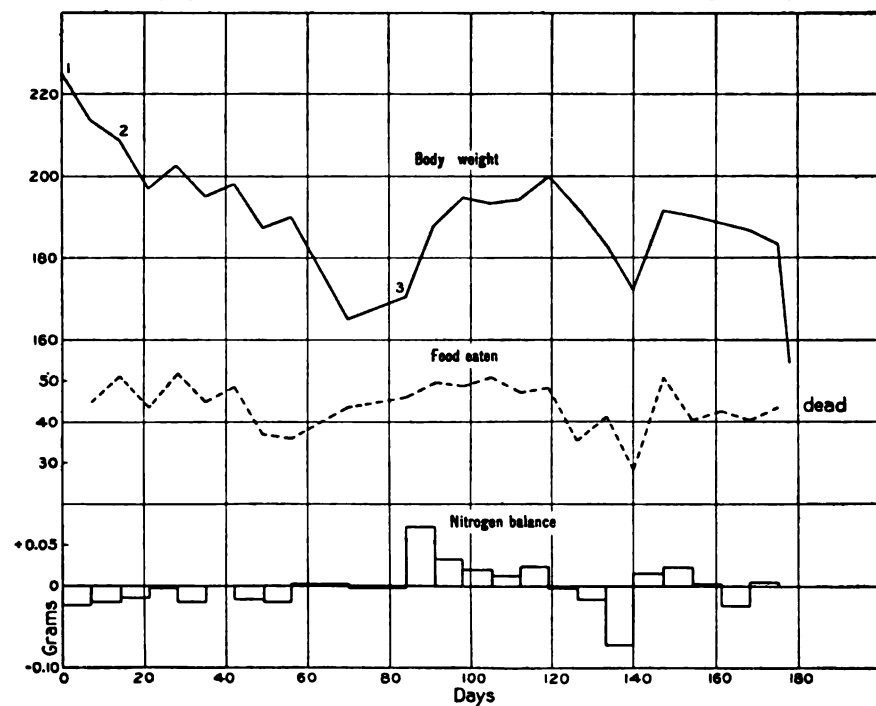
CHART IX.—Rat 11 fed on Dog Biscuit-Lard Diet for 84 days and then on Milk powder-Starch-Lard Diet for 94 days. Numbers on Body-weight line indicate time at which each period began.
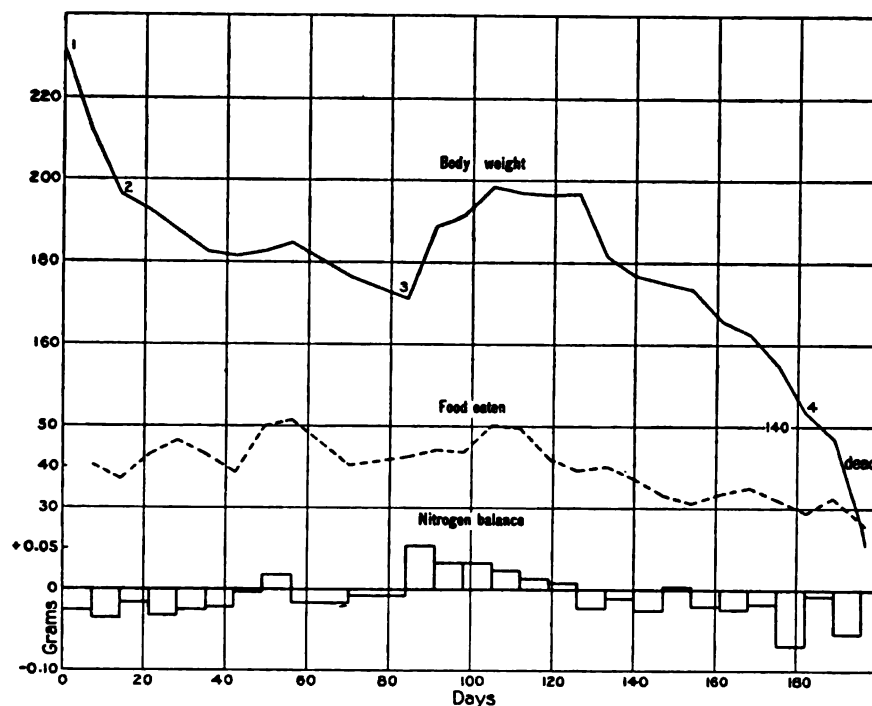
CHART X.—Rat 12, fed on Dog Biscuit-Lard Diet for 84 days and then on Milk powder-Starch-Lard Diet for 113 days. Numbers on Body-weight line indicate time at which each period began.

DISCUSSION.

The rats XXVIII and XXIX showed a steady decline on the dog-biscuit-fat mixture (p. 13). In considering the quantity of food eaten it must be borne in mind that the nitrogen content was rather low (N = 1.65 per cent).

Rats 10, 11, and 12 also showed, during the early period of the experiment, a steady decline on the same diet, although it contained more nitrogen. The temporary improvement shown after several weeks at the point marked 3 indicates the introduction of a change in diet. The improvement was, however, only temporary, as the charts indicate. The curves of body-weight in these animals recall those published by Falta and Noegerrath and correspond with the data of other investigators mentioned above. They indicate the type of experiment which is unsuccessful because of more or less obvious insufficiency in food-intake or stored supply. In the case of rats XXVIII and 10, for example, this is pronounced and a steady and continuous decline is noted. The decline of rat XXIX, at first gradual, became extremely marked with the striking decrease in the food-intake at the end of the experiment. The other illustrations (rats 11 and 12) show intermediate types. As a rule, older, full-grown animals exhibit slower decline than younger rats (of smaller weight)

because of the greater store of fat, etc. This helps to explain the long period of survival noted by various earlier investigators who have usually employed older (mature) animals for their feeding trials.

THE CASEIN DIET. PRELIMINARY TRIALS.

More experiments of this sort have been carried on with casein than with any other protein as the sole nitrogenous component. It can readily be isolated in a state of comparative purity; and inasmuch as it contains phosphorus in an organic complex, known by long experience to be assimilable, one of the problematical features pertaining to most other proteins is eliminated by its use. Our efforts have been directed toward finding a diet containing casein as the sole protein and which might meet the requirements of a long-continued experiment. In this we have been to a large degree successful in the case of mature rats.

Our earlier trials were conducted with a variety of food-mixtures containing casein. It was soon apparent that the protein requirement of the animals can be satisfied with comparative ease; accordingly the ration was prepared with a nitrogen concentration of about 2.5 per cent. The necessity for the use of much fat to insure the requisite paste consistency (and thus avoid scattering of the food) has put distinct limitations on the range of choice. We have tried without success to avoid the use of so much fat. To indicate the variety and proportion of inorganic elements which we have attempted to introduce, some of the mixtures are given in table XII.

TABLE XII.

Salt mixture I (Röhmann).	grams.	Salt mixture II (McCollum).	grams.	Salt mixture III.	grams.
$Ca_3(PO_4)_2$	10.0	Ash of milk	60.6	NaCl	33.4
K_2HPO_4	37.0	$Ca_3(PO_4)_2$	24.2	KCl	33.4
NaCl	20.0	NaCl	12.1	Bone ash	25.1
Na citrate	15.0	Fe citrate	3.1	Na_2CO_3	6.7
Mg citrate	8.0			Fe citrate	1.4
Ca lactate	8.0		100.0		
Fe citrate	2.0				100.0
	100.0				

It is still debatable whether any "roughage," such as cellulose, is absolutely necessary. McCollum[*] fed egg-yolk alone to white rats for 18 weeks without unfavorable results. Nevertheless we have introduced an indigestible residue as conforming more nearly to the usual alimentary experience of the animals; and agar-agar was selected because it is more easily manipulated than cellulose and because experience with other animals has shown us how efficient it is for this purpose.[†]

[*] McCollum: American Journal of Physiology, 1909, xxv, p. 127.
[†] Cf. Saiki: Journal of Biological Chemistry, 1906, II, p. 251. Swartz: Transactions of the Connecticut Academy of Arts and Sciences, 1911, xvi, p. 247. Mendel and Swartz: American Journal of Medical Sciences, March, 1910.

In order to compare the suitability of casein diets containing the salt mixtures recorded above, a series of trials was begun on rats which had previously been under observation in cages so that any eccentricity of eating or of metabolism might be noted. During this preliminary period the diet consisted of the dog biscuit mixture already referred to in the "control" series. During the casein periods the following diets were used, which are indicated in the tables by the corresponding numbers.

TABLE XIII.

	1	2	3	4	5	6
Pure casein	13.4	18.0	10.0	18.0	12.0	18.0
Cane sugar	20.6	15.0	4.0	15.0	15.0	15.0
Starch (arrow-root)	23.7	29.5	46.0	29.5	30.0	29.5
Lard	35.0	30.0	30.8	30.0	30.0	30.0
Agar	5.2	5.0	4.4	5.0	5.0	5.0
Salt mixture I			4.8	2.5		
Salt mixture II					8.0	2.5
Salt mixture III	2.1	2.5				
	100.0	100.0	100.0	100.0	100.0	100.0
Nitrogen	1.87	2.51	1.38	2.54	1.54	2.53

The records of the animals during the entire course of the experiment, until it was stopped by the loss of the laboratory by fire, are shown in Tables XIV–XXII and Charts XI–XIII.

TABLE XIV.—SUMMARY OF DATA ON RAT XXX, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE III FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 1	159.0							
8	178.8	9.8	0.158	0.139	0.019	0.158	88	0.000
15	191.3	10.8	0.180	0.119	0.032	0.151	82	+0.029
22	185.6	9.3	0.154	0.114	0.028	0.142	82	+0.012

PERIOD 2.—CASEIN DIET 1.

1909.								
Nov. 29	167.0	5.1	0.096	0.091	0.023	0.114	76	−0.018
Dec. 6	166.1	6.0	0.112	0.091	0.020	0.111	82	+0.001
13	162.7	5.4	0.101	0.091	0.015	0.106	85	−0.005

PERIOD 3.—CASEIN DIET 2.

1909.								
Dec. 20	164.5	5.7	0.144	0.123	0.015	0.138	90	+0.006
27	170.1	6.5	0.164	0.139	0.014	0.153	91	+0.011
1910.								
Jan. 3	174.3	7.1	0.180	0.149	0.017	0.166	91	+0.014

TABLE XV.—SUMMARY OF DATA ON RAT XXXI, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE III FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 1....	181.7	....						
8....	204.2	10.8	0.173	0.140	0.025	0.165	86	+0.008
15....	204.5	8.2	0.136	0.107	0.011	0.118	92	+0.018
22....	197.1	7.7	0.128	0.113	0.024	0.137	81	—0.009

PERIOD 2.—CASEIN DIET 1.

1909.								
Nov. 29....	184.1	4.7	0.089	0.089	0.018	0.107	80	—0.018
Dec. 6....	186.1	6.9	0.129	0.089	0.022	0.111	83	+0.018
13....	199.7	9.0	0.168	0.092	0.033	0.125	80	+0.043

PERIOD 3.—CASEIN DIET 2.

1909.								
Dec. 20....	208.5	7.9	0.199	0.111	0.023	0.134	82	+0.065
27....	202.7	9.4	0.237	0.160	0.026	0.186	89	+0.051
1910.								
Jan. 3....	198.5	6.5	0.164	0.146	0.030	0.176	82	—0.012

TABLE XVI.—SUMMARY OF DATA ON RAT XXXII, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE III FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 1....	180.5	....						
8....	196.7	9.3	0.148	0.145	0.017	0.162	89	—0.014
15....	200 3	7.4	0.120	0.099	0.020	0.119	83	+0.001
22....	201.4	9.2	0.152	0.111	0.034	0.145	78	+0.007

PERIOD 2.—CASEIN DIET 1.

1909.								
Nov. 29....	193.7	6.1	0.113	0.095	0.018	0.113	84	0.000
Dec. 6....	189.6	5.8	0.109	0.089	0.020	0.109	82	0.000
13....	191.2	7.1	0.133	0.093	0.024	0.117	82	+0.016

PERIOD 3.—CASEIN DIET 2.

1909.								
Dec. 20....	193.8	6.1	0.153	0.113	0.015	0.128	90	+0.025
27....	199.3	7.6	0.192	0.154	0.018	0.172	91	+0.020
1910.								
Jan. 3....	204.7	7.8	0.198	0.160	0.020	0.180	90	+0 018

TABLE XVII.—SUMMARY OF DATA ON RAT XXXIII, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE I FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 1....	206.0	......	......	......	......	......	......	......
8....	220.2	8.4	0.135	0.138	0.023	0.161	83	—0.026
15....	226.3	8.6	0.137	0.116	0.021	0.137	85	0.000
22....	220.2	8.2	0.136	0.127	0.026	0.153	81	—0.017

PERIOD 2.—CASEIN DIET 3.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Nov. 29....	205.5	5.6	0.077	0.086	0.023	0.109	70	—0.032
Dec. 6....	199.2	6.9	0.095	0.071	0.042	0.113	56	—0.018

PERIOD 3.—CASEIN DIET 4.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Dec. 13....	206.3	7.5	0.156	0.092	0.034	0.126	78	+0.030
20....	219.5	8.8	0.223	0.102	0.033	0.135	85	+0.088
27....	226.8	9.5	0.240	0.165	0.040	0.205	83	+0.035
1910.								
Jan. 3....	233.0	9.4	0.235	0.168	0.015	0.183	94	+0.052

TABLE XVIII.—SUMMARY OF DATA ON RAT XXXIV, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE I FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 8....	157.0	......	......	......	......	......	......	......
15....	170.4	9.3	0.157	0.124	0.030	0.154	81	+0.003
22....	169.3	8.2	0.137	0.092	0.030	0.122	78	—0.015

PERIOD 2.—CASEIN DIET 3.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Nov. 29....	164.2	5.9	0.081	0.067	0.017	0.084	79	—0.003
Dec. 6....	157.5	5.9	0.081	0.064	0.024	0.088	70	—0.007

PERIOD 3.—CASEIN DIET 4.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Dec. 13....	172.5	8.0	0.172	0.080	0.036	0.116	79	+0.056
20....	181.8	7.8	0.199	0.108	0.039	0.147	80	+0.052
27....	198.5	9.4	0.236	0.127	0.039	0.166	83	+0.070
1910.								
Jan. 3....	206.2	9.0	0.226	0.125	0.047	0.172	79	+0.054

TABLE XIX.—SUMMARY OF DATA ON RAT XXXV, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE I FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 8....	116.5							
15....	122.7	6.5	0.110	0.101	0.020	0.121	82	—0.011
22....	126.2	6.2	0.102	0.074	0.017	0.091	83	+0.011

PERIOD 2.—CASEIN DIET 3.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Nov. 29....	111.4	4.0	0.055	0.052	0.020	0.072	64	—0.017
Dec. 6....	118.3	4.5	0.062	0.050	0.014	0.064	77	—0.002

PERIOD 3.—CASEIN DIET 4.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Dec. 13....	127.1	6.1	0.126	0.060	0.028	0.088	78	+0.038
20....	142.9	8.8	0.225	0.105	0.025	0.130	89	+0.095
27....	147.3	7.2	0.181	0.116	0.029	0.145	84	+0.036
1910.								
Jan. 3....	152.5	6.7	0.167	0.108	0.026	0.134	84	+0.033

TABLE XX.—SUMMARY OF DATA ON RAT XXXVII, FED ON PURE CASEIN (AS THE ONLY PROTEIN) AND SALT MIXTURE II FOR 42 DAYS.—DAILY AVERAGES.

PERIOD 1.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 8....	142.7							
15....	153.2	8.7	0.146	0.115	0.023	0.138	84	+0.008
22....	156.3	7.8	0.128	0.091	0.026	0.117	80	+0.011

PERIOD 2.—CASEIN DIET 5.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Nov. 29....	136.7	4.6	0.070	0.072	0.024	0.096	66	—0.026
Dec. 6....	136.0	5.7	0.088	0.071	0.034	0.105	61	—0.017

PERIOD 3.—CASEIN DIET 6.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1909.								
Dec. 13....	135.5	5.6	0.116	0.085	0.025	0.110	78	+0.006
20....	137.5	7.3	0.184	0.109	0.021	0.130	89	+0.054
27....	140.8	6.2	0.159	0.122	0.024	0.146	85	+0.013
1910.								
Jan. 3....	143.3	5.9	0.151	0.121	0.021	0.142	86	+0.009

Table XXI.—Summary of Data on Rat XL, fed on Pure Casein (as the only Protein) and Salt Mixture II for 42 Days.—Daily Averages.

Period 1.—Dog Biscuit-Lard Diet.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Faeces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 10....	150.0							
15....	135.4	2.7	0.045	0.106	0.007	0.113	84	−0.068
22....	147.3	7.7	0.130	0.096	0.021	0.117	84	+0.013

Period 2.—Casein Diet 5.

1909.								
Nov. 29....	137.8	4.6	0.071	0.059	0.020	0.079	82	−0.008
Dec. 6....	138.5	6.3	0.100	0.068	0.033	0.101	67	−0.001

Period 3.—Casein Diet 6.

1909.								
Dec. 13....	139.5	6.1	0.129	0.088	0.027	0.115	79	+0.014
20....	130.0	4.3	0.109	0.099	0.019	0.118	83	−0.009
27....	115.6	3.4	0.087	0.102	0.014	0.116	84	−0.029
1910.								
Jan. 3....	110.0	4.0	0.103	0.105	0.017	0.122	83	−0.019

Table XXII.—Summary of Data on Rat XLII, fed on Pure Casein (as the only Protein) and Salt Mixture II for 42 Days.—Daily Averages.

Period I.—Dog Biscuit-Lard Diet.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Faeces.	Total.		
1909.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Nov. 10....	144.0							
15....	137.8	4.9	0.082	0.090	0.013	0.103	84	−0.021
22....	141.4	6.3	0.106	0.069	0.020	0.089	81	+0.017

Period 2.—Casein Diet 5.

1909.								
Nov. 29....	130.2	3.8	0.059	0.062	0.019	0.081	68	−0.022
Dec. 6....	130.6	5.6	0.086	0.072	0.031	0.103	64	−0.017

Period 2.—Casein Diet 6.

1909.								
Dec. 13....	126.4	4.8	0.101	0.086	0.022	0.108	78	−0.007
20....	128.4	5.0	0.126	0.105	0.021	0.126	83	0.000
27....	122.4	4.7	0.120	0.108	0.023	0.131	81	−0.011
1910.								
Jan. 3....	116.2	4.4	0.113	0.109	0.025	0.134	78	−0.021
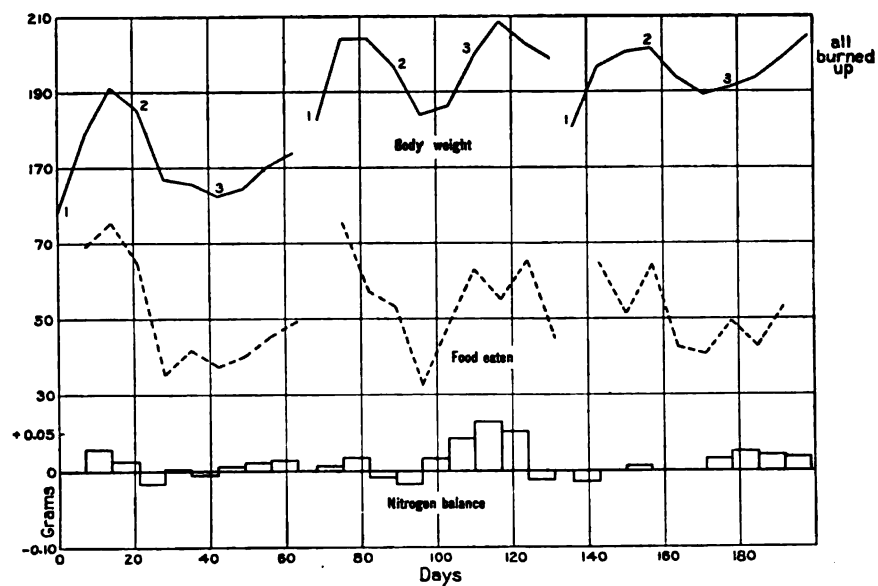
CHART XI.—Rats xxx, xxxi, and xxxii fed on pure Casein as the only protein and Salt mixture III for 42 days. Numbers on Body-weight line indicate the time at which each period began.
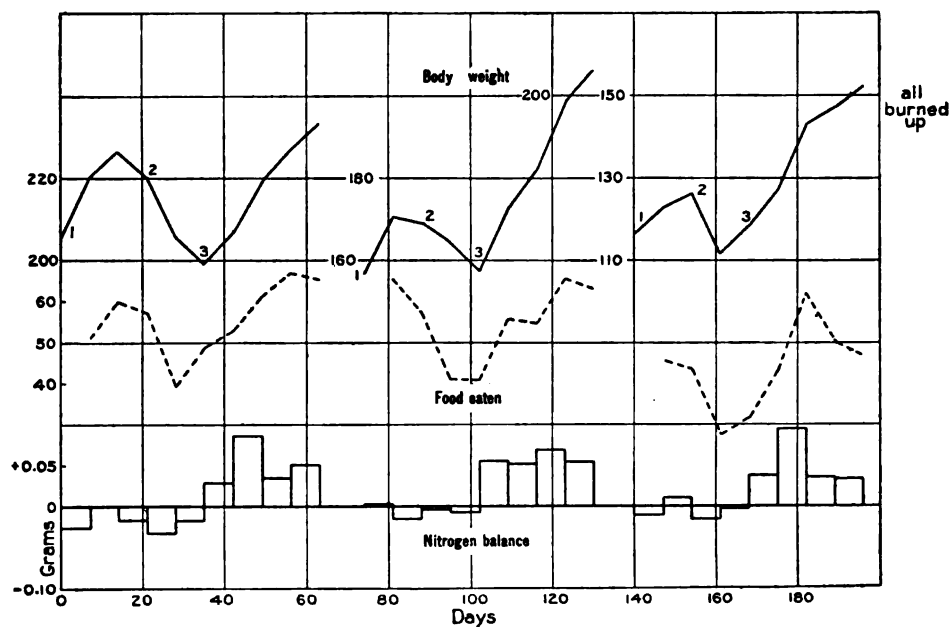
CHART XII.—Rats xxxiii, xxxiv, and xxxv fed on pure Casein as the only protein and Salt mixture I for 42 days. Numbers on Body-weight line indicate time at which each period began.
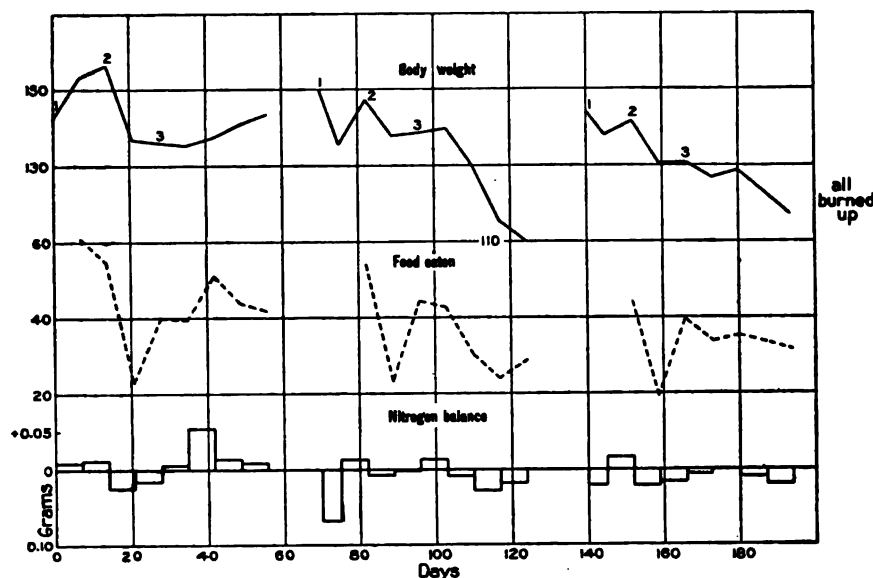
CHART XIII.—Rats XXXVII, XL, and XLII fed on pure Casein as the only protein and Salt Mixture II for 42 days. Numbers on Body-weight lines indicate time at which each period began.

DISCUSSION.

The essential differences in these series lasting 42 days involve the inorganic constituents of the diet. All of the animals selected, with two exceptions (XL and XLII)* gave a fairly satisfactory record during a three weeks preliminary trial, whereupon they were selected for the casein feeding. It will be seen that the most promising nutritive conditions were afforded by mixture I, fed to rats XXXIII, XXXIV, and XXXV, in which the inorganic constituents were closely copied after Röhmann's successful ash mixture, with the addition of a little iron. During the first two weeks of casein feeding these three rats lost weight and nitrogen. This was caused by diarrhœa due to too great a proportion of inorganic salts in the food mixture. When this was reduced from 4.8 to 2.5 per cent a very rapid gain in weight and nitrogen at once took place. The superiority of the food mixture given to these three rats in contrast with the other two mixtures given to the other rats is plainly evident from comparison of these data. These experiments lasted 42 days and showed distinct gains in the nitrogen balance and also in body-weight during the period mentioned.†

*These two animals were not pure white rats, but partly colored. They ate very poorly. We have gained the impression from observations on a large number of rats that these hybrid forms are not suited to our experimental needs and therefore have lately employed only the pure white races.

†It may be noted that the *apparently* poorer utilization of nitrogen during some of the periods when little food was eaten is in part attributable to the fact that output of nitrogenous alimentary secretions continues despite the smaller intake of nitrogen.

THE CASEIN DIET—PROLONGED FEEDING TRIALS.

The proportions of this food mixture (4, see page 33) thus tested were therefore employed in subsequent experiments as a typical "basal" ration. We record below the protocols of a few rats which for many weeks have been kept in good health on this dietary with pure casein as the sole protein.

By an ill-advised plan these casein-fed rats were transferred during one month to cages containing sand, and the estimation of the nitrogenous excreta was omitted during this period. It was subsequently discovered that the animals ate more or less sand during this time and we attribute the decline of weight and the subsequent death in some cases to a resulting damage of the alimentary organs, since sand was found in the fæces of some of the rats long afterwards and autopsy showed great congestion of the intestinal tract.

TABLE XXIII.—SUMMARY OF DATA ON RAT 23, FED FOR 135 DAYS ON PURE CASEIN AS THE ONLY PROTEIN.—DIET 4, PAGE 33.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Feb. 7....	195.7							
14....	209.3	8.0	0.208	0.111	0.026	0.137	87	+0.071
21....	222.0	9.4	0.247	0.118	0.041	0.159	83	+0.088
28....	220.5	8.1	0.215	0.108	0.039	0.147	82	+0.068
Mar. 7....	212.8	7.0	0.186	0.141	0.031	0.172	83	+0.014
14....	210.0	6.6	0.173	0.145	0.024	0.169	86	+0.004
28....	221.1	7.9	0.209	0.155	0.029	0.184	86	+0.025
Apr. 11....	232.0	7.9	0.208	0.147	0.030	0.177	86	+0.031
18....	234.4	9.1						
25....	217.6	5.9						
May 2....	201.8	4.7						
9....	211.3	5.4						
16....	219.0	7.2	0.185	0.112	0.027	0.139	85	+0.046
23....	225.0	7.7	0.197	0.137	0.028	0.165	86	+0.032
30....	220.8	6.6	0.168	0.131	0.026	0.157	85	+0.011
June 6....	225.6	7.9	0.201	0.140	0.029	0.169	86	+0.032
13....	212.3	6.2	0.158	0.155	0.025	0.180	84	-0.022
20....	197.0	4.9	0.126	0.146	0.017	0.163	87	-0.037
22....	182.7							
Dead								

TABLE XXIV.—SUMMARY OF DATA ON RAT 24, FED FOR 169 DAYS ON PURE CASEIN AS THE ONLY PROTEIN.—DIET 4, PAGE 33.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Feb. 7....	227.0							
14....	239.0	8.6	0.226	0.145	0.023	0.168	90	+0.058
21....	244.0	10.1	0.266	0.180	0.039	0.219	85	+0.047
28....	239.0	9.4	0.248	0.192	0.037	0.229	85	+0.019
Mar. 7....	241.0	8.2	0.217	0.180	0.022	0.202	90	+0.015
14....	242.0	8.8	0.234	0.181	0.032	0.213	86	+0.021
28....	259.6	9.6	0.254	0.195	0.031	0.226	88	+0.028
Apr. 11....	252.7	9.0	0.235	0.176	0.032	0.208	86	+0.027
18....	235.8	6.5						
25....	218.8	4.6						
May 2....	205.2	4.5						
9....	214.8	5.8						
16....	216.1	7.0	0.178	0.123	0.029	0.152	84	+0.026
23....	240.5	9.5	0.242	0.150	0.030	0.180	88	+0.062
30....	252.4	9.1	0.233	0.163	0.023	0.186	90	+0.047
June 6....	257.1	8.8	0.226	0.161	0.024	0.185	89	+0.041
13....	248.7	7.3	0.188	0.163	0.021	0.184	89	+0.004
20....	243.6	6.7	0.172	0.155	0.018	0.173	90	-0.001
27....	246.6	6.4	0.164	0.142	0.014	0.156	91	+0.008
July 4....	243.5	7.3	0.184	0.152	0.018	0.170	90	+0.014
11....	244.1	8.2	0.209	0.166	0.031	0.197	85	+0.012
18....	230.0	8.6	0.220	0.133	0.049	0.182	78	+0.038
25....	169.1	1.6	0.042	0.103	0.037	0,140	12	-0.098
26....	157.3							
Chlorof'd.....								

TABLE XXV.—SUMMARY OF DATA ON RAT 25, FED FOR 176 DAYS ON PURE CASEIN AS THE ONLY PROTEIN.—DIET 4, PAGE 33.—DAILY AVERAGES.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Feb. 7....	177.0							
14....	189.0	9.6	0.252	0.170	0.034	0.204	87	+0.048
21....	184.6	7.8	0.207	0.164	0.033	0.197	84	+0.010
28....	199.5	9.3	0.245	0.176	0.021	0.197	91	+0.048
Mar. 7....	198.3	9.0	0.238	0.175	0.033	0.208	86	+0.030
14....	199.2	7.9	0.210	0.181	0.029	0.210	86	0.000
28....	199.0	7.9	0.210	0.176	0.026	0.202	88	+0.008
Apr. 11....	198.2	7.5	0.196	0.159	0.031	0.190	84	+0.006
18....	200.6	9.1						
25....	187.2	5.4						
May 2....	167.3	3.9						
9....	179.2	6.3						
16....	181.0	6.3	0.161	0.125	0.020	0.145	88	+0.016
23....	186.0	7.1	0.180	0.126	0.029	0.155	84	+0.025
30....	190.5	7.2	0.185	0.138	0.024	0.162	87	+0.023
June 6....	196.1	8.5	0.219	0.149	0.022	0.171	90	+0.048
13....	191.0	7.1	0.181	0.154	0.024	0.178	87	+0.003
20....	185.0	6.3	0.160	0.146	0.023	0.169	86	-0.009
27....	185.0	6.2	0.157	0.124	0.023	0.147	85	+0.010
July 4....	177.6	4.9	0.125	0.106	0.025	0.131	80	-0.006
11....	165.8	3.7	0.095	0.098	0.015	0.113	84	-0.018
18....	153.5	3.1	0.078	0.076	0.014	0.090	82	-0.012
25....	140.5	3.3	0.084	0.090	0.017	0.107	80	-0.023
Aug. 1....	110.0	2.0	0.052	0.086	0.018	0.104	65	-0.052
Dead 2....	107.0							
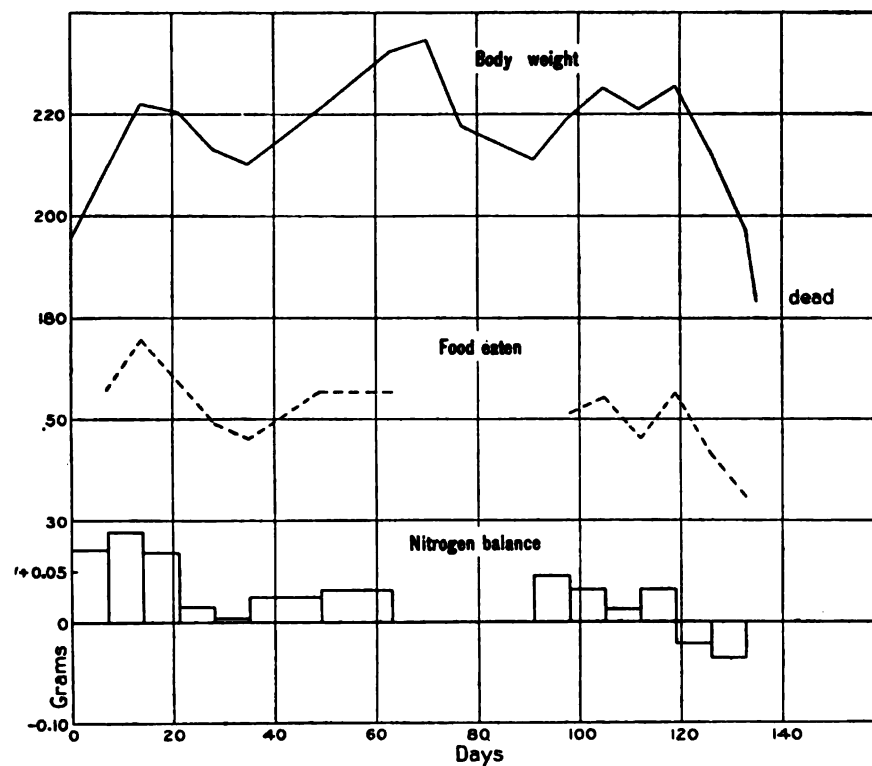
Chart XIV.—Rat 23 fed 135 days on pure Casein as the only protein, Diet 4, p. 33.
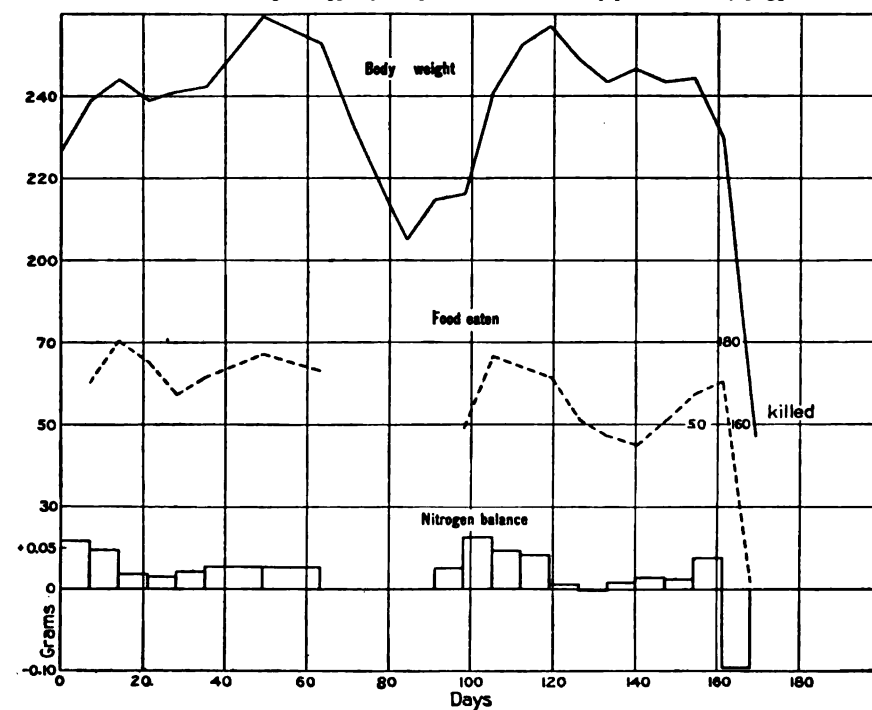
Chart XV.—Rat 24 fed 169 days on pure Casein as the only protein, Diet 4, p. 33.
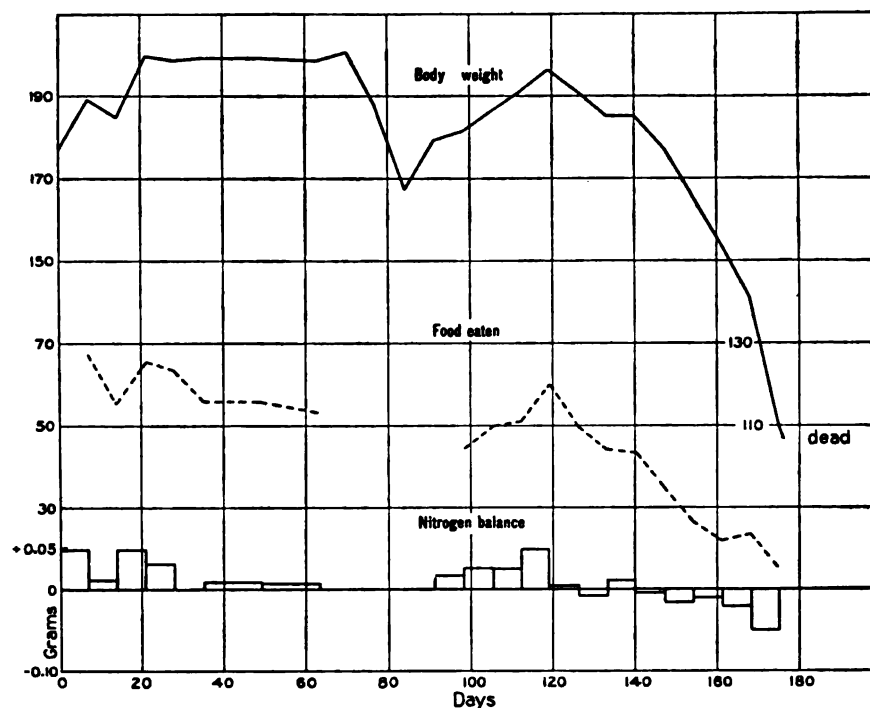
CHART XVI.—Rat 25 fed 176 days on pure Casein as the only protein, Diet 4, p. 33.

These experiments, with rats 23, 24 and 25, extending over 135–160 days without noteworthy alterations in the weight and with a very large gain of nitrogen, are, as far as we are aware, the most successful recorded attempts at artificial nutrition with a constant mixture of pure food-stuffs including a single protein.

CASEIN AND VEGETABLE PROTEIN DIET.

Without reporting here the numerous trials and failures to replace part or all of the casein by other proteins, a few data from our records may throw light upon the difficulties thus encountered. The proportion of the nutrients is the same in these experiments, one-third or more of the casein being replaced by the proteins indicated.

A casual inspection of the succeeding pages shows that the failure to eat is frequently sufficient to account for the failure to maintain body-weight and tissue. The animals lost weight to the extent of their fat content and then speedily succumbed with indications of inanition rather than any specific pathological metabolism. Those rats which ate less than 40 grams of the mixed food were unable to maintain their nutritive equilibrium. A further evidence that no permanent defect is induced by the character of the diet is found in the observation that a change to a mixed diet of seeds and vegetables often brought speedy realimentation and recovery.

Despite numerous failures with other proteins than casein, several experiments have already been continued long enough to hold out promise of the possibility of ultimate success. In these the animals were fed on a mixture in which the casein content was gradually decreased and then entirely replaced by vegetable protein.*

RAT 16.—This rat, after a preliminary feeding on dog biscuit-lard diet, was fed through Period 2 with a mixture containing casein 12, excelsin 6, sugar 15, starch 29.5, lard 30, agar 5 and salt mixture I 2.5 per cent. This contained 2.74 per cent of nitrogen. During Period 3 the proportions of excelsin and casein were 9 per cent, the rest of the mixture remaining the same and containing 2.75 per cent of nitrogen. During Period 4 the proportion of excelsin was made 12 and casein 6 per cent, and the diet (otherwise as before) contained 2.8 per cent of nitrogen. Throughout Period 5 the casein was wholly replaced by excelsin, but otherwise the mixture was that above given. The nitrogen content of this diet was 2.94 per cent.

TABLE XXVI.—SUMMARY OF DATA ON RAT 16, FED FOR 210 DAYS ON MIXTURES CONTAINING CASEIN AND EXCELSIN AS THE ONLY PROTEINS.—DAILY AVERAGES.

PERIOD 1, 28 DAYS.—DOG BISCUIT-LARD DIET.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Jan. 24....	238.8	......	......				......	......
31....	235.2	8.4	0.132	0.103	0.025	0.128	81	+0.004
Feb. 7....	225.0	6.5	0.106	0.084	0.024	0.108	77	−0.002
14....	226.8	8.5	0.163	0.102	0.029	0.131	82	+0.032
21....	219.5	5.7	0.110	0.088	0.018	0.106	84	+0.004

PERIOD 2, 42 DAYS.—CASEIN 12 PER CENT, EXCELSIN 6 PER CENT.

1910.								
Feb. 28....	227.8	6.1	0.164	0.141	0.017	0.158	90	+0.006
Mar. 7....	230.0	7.8	0.211	0.150	0.033	0.183	84	+0.028
14....	225.6	7.0	0.189	0.154	0.029	0.183	85	+0.006
21....	226.8	6.6	0.180	0.128	0.018	0.146	90	+0.034
28....	234.0	7.4	0.205	0.156	0.024	0.180	88	+0.025
Apr. 4....	227.8	6.9	0.191	0.148	0.026	0.174	86	+0.017

PERIOD 3, 35 DAYS.—CASEIN 9 PER CENT, EXCELSIN 9 PER CENT.

1910.								
Apr. 11....	225.5	7.5	0.207	0.160	0.031	0.191	85	+0.016
18....	224.0	7.0	0.193	0.180	0.021	0.201	89	−0.008
25....	229.5	7.6	0.211	0.172	0.023	0.195	89	+0.016
May 2....	234.2	8.5	0.234	0.169	0.027	0.196	88	+0.038
9....	240.0	8.7	0.238	0.175	0.025	0.200	89	+0.038

*For a description of the vegetable proteins used see Osborne; Die Pflanzenproteine, Ergebnisse der Physiologie, 1910, X, p. 47.

TABLE XXVI.—SUMMARY OF DATA ON RAT 16, FED FOR 210 DAYS ON MIXTURES CONTAINING CASEIN AND EXCELSIN AS THE ONLY PROTEINS.—DAILY AVERAGES.—Cont'd.

PERIOD 4, 14 DAYS.—CASEIN 6 PER CENT, EXCELSIN 12 PER CENT.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
May 16....	232.1	7.5	0.210	0.167	0.028	0.195	87	+0.015
23....	233.5	7.2	0.201	0.177	0.020	0.197	90	+0.004

PERIOD 5, 119 DAYS.—EXCELSIN 18 PER CENT.

Date of experiment.	Body-weight.	Food.	Nitrogen.	Urine.	Fæces.	Total.	N-utilization.	N-balance.
1910.								
May 30....	235.6	7.2	0.215	0.165	0.024	0.189	89	+0.024
June 6....	235.0	8.1	0.238	0.192	0.020	0.212	92	+0.026
13....	231.8	7.2	0.211	0.192	0.022	0.214	90	−0.003
20....	228.5	7.3	0.215	0.173	0.026	0.199	88	+0.016
27....	218.9	4.7	0.139	0.141	0.015	0.156	89	−0.017
July 4....	216.2	7.4	0.217	0.150	0.025	0.175	88	+0.042
11....	216.5	6.3	0.186	0.155	0.020	0.175	89	+0.011
18....	220.7	7.6	0.225	0.158	0.025	0.183	89	+0.042
25....	207.5	6.6	0.193	0.181	0.027	0.208	86	−0.015
Aug. 1....	214.5	7.3	0.214	0.159	0.017	0.176	92	+0.038
8....	220.0	7.9	0.231	0.141	0.016	0.157	93	+0.074
15....	212.7	8.2	0.242	0.196	0.025	0.221	90	+0.021
22....	219.4	8.3	0.244	0.170	0.020	0.190	92	+0.054
29....	216.3	8.6	0.252	0.159	0.025	0.184	90	+0.068
Sept. 5....	209.5	8.9	0.262	0.212	0.037	0.249	86	+0.013
12....	197.0	7.9	0.234	0.229	0.022	0.251	91	−0.017
19....	160.3	6.1	0.180	0.223	0.039	0.262	78	−0.082
Dead								

CHART XVII.—Rat 16 fed 210 days on Casein and Excelsin as the only proteins. See p. 44. Numbers on Body-weight line indicate time at which each period began.

RAT 70.—This rat was fed during Period 1 with a mixture containing casein 9, pea legumin 9, sugar 15, starch 29.5, lard 30, agar 5, and salt mixture No. 1, containing 2.5 per cent. This contained 2.75 per cent of nitrogen. During Period 2, the diet contained 18 per cent of legumin as the only protein, the proportion of the other constituents being unchanged. The nitrogen content was 2.97 per cent.
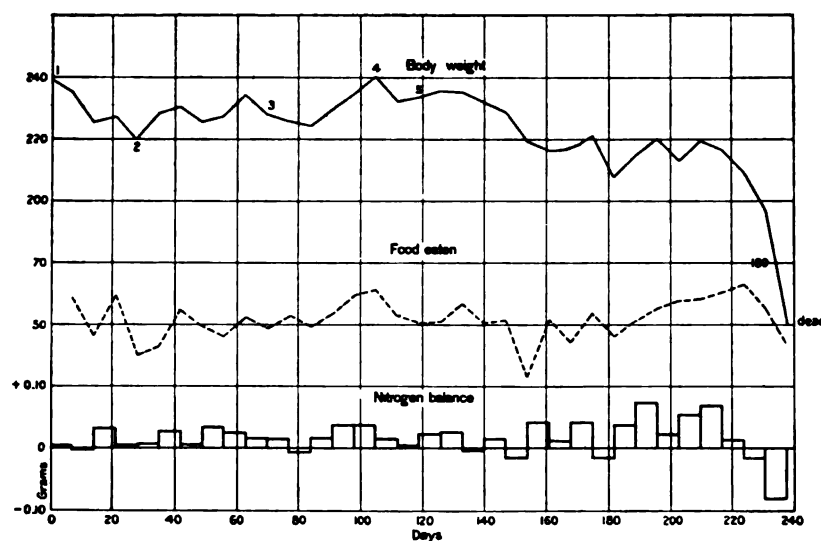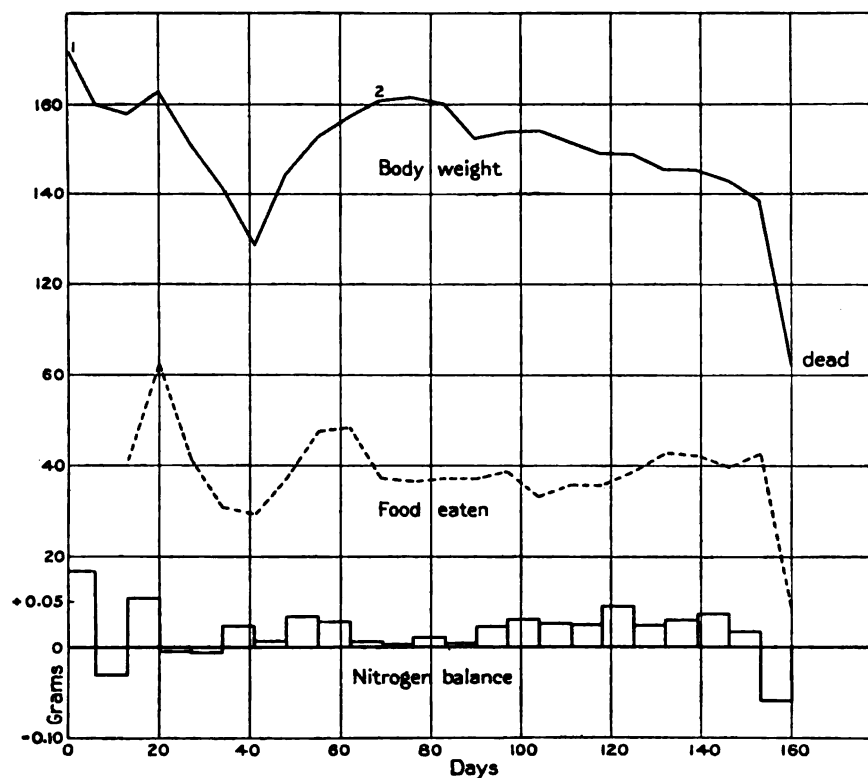

CHART XVIII.—Rat 70, fed 160 days on Casein and Pea-Legumin as the only proteins.
See p. 47. Numbers on Body-weight line indicate time at which each period began.

Table XXVII.—Summary of Data on Rat 70, fed for 160 Days on Mixtures Containing Casein and Pea Legumin as the Only Proteins.—Daily Averages.

Period 1, 69 Days.—Casein 9 per cent, Pea Legumin 9 per cent.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Apr. 5....	171.7							
11....	160.0	9.6	0.267	0.159	0.026	0.185	90	+0.082
18....	157.8	5.9	0.164	0.181	0.015	0.196	91	—0.032
25....	162.5	8.9	0.249	0.179	0.016	0.195	94	+0.054
May 2....	151.0	5.9	0.164	0.153	0.016	0.169	90	—0.005
9....	141.2	4.4	0.122	0.118	0.011	0.129	91	—0.007
16....	128.6	4.2	0.115	0.075	0.017	0.092	85	+0.023
23....	144.5	5.3	0.145	0.130	0.009	0.139	94	+0.006
30....	152.8	6.8	0.186	0.131	0.022	0.153	88	+0.033
June 6....	157.8	6.9	0.187	0.139	0.021	0.160	89	+0.027
13....	160.6	5.3	0.143	0.124	0.015	0.139	90	+0.004

Period 2, 91 Days.—Pea Legumin 18 per cent.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
1910.								
June 20....	161.3	5.2	0.155	0.141	0.013	0.154	92	+0.001
27....	160.0	5.3	0.158	0.128	0.020	0.148	87	+0.010
July 4....	152.3	5.3	0.156	0.134	0.019	0.153	88	+0.003
11....	153.8	5.5	0.163	0.125	0.017	0.142	90	+0.021
18....	154.0	4.7	0.140	0.096	0.014	0.110	90	+0.030
25....	151.5	5.1	0.151	0.107	0.019	0.126	87	+0.025
Aug. 1....	149.0	5.0	0.150	0.111	0.015	0.126	90	+0.024
8....	148.7	5.5	0.163	0.103	0.116	0.119	90	+0.044
15....	145.3	6.1	0.180	0.140	0.018	0.158	90	+0.022
22....	145.5	6.0	0.179	0.133	0.017	0.150	91	+0.029
29....	142.6	5.7	0.168	0.116	0.017	0.133	90	+0.035
Sept. 5....	138.5	6.0	0.176	0.135	0.025	0.160	86	+0.016
12....	102.0	1.2	0.034	0.082	0.013	0.095	62	—0.061
Dead								

Rat 71.—This rat was fed during Period 1 with a mixture containing casein 12, glutenin 6, sugar 15, starch 29.5, lard 30, agar 5, salt mixture I 2.5 per cent. This contained 2.69 per cent nitrogen. During Period 2 the diet contained casein 12, glutenin 6, sugar 15, starch 24.5, lard 35, agar 5, salt mixture I 2.5 per cent, with 2.68 per cent of nitrogen. During Period 3 the diet consisted of glutenin 16.4, sugar 13.6, starch 22.3, lard 40.9, agar 4.5, salt mixture I 2.3 per cent, and contained 2.60 per cent of nitrogen. Throughout Period 4, the diet contained glutenin 18, sugar 15, starch 14.5, lard 45, agar 5 and salt mixture I 2.5 per cent. This diet contained 2.83 per cent of nitrogen which belonged wholly to glutenin.

Rat 71 is still alive at the present writing after 217 days of exclusive diet containing glutenin as its only protein, and 286 days including the casein and glutenin period.

TABLE XXVIII.—SUMMARY OF DATA ON RAT 71, FED FOR 244 DAYS ON MIXTURES CONTAINING CASEIN AND GLUTENIN AS THE ONLY PROTEINS.—DAILY AVERAGES.

PERIOD 1, 13 DAYS.—CASEIN 12 PER CENT, GLUTENIN 6 PER CENT.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.*
		Food.	Nitrogen.	Urine.	Faeces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Apr. 5....	257.5							
18....	210.5	6.8	0.184	0.183	0.030	0.213	84	—0.029

PERIOD 2, 56 DAYS.—CASEIN 12 PER CENT, GLUTENIN 6 PER CENT.

1910.								
Apr. 25....	238.7	11.0	0.297	0.249	0.031	0.280	90	+0.017
May 2....	225.5	4.6	0.124	0.187	0.013	0.200	90	—0.076
9....	222.2	9.6	0.259	0.163	0.017	0.180	93	+0.079
16....	227.1	6.1	0.166	0.130	0.014	0.144	92	+0.022
23....	234.5	7.3	0.196	0.139	0.020	0.159	90	+0.037
30....	242.3	8.2	0.218	0.152	0.025	0.177	89	+0.041
June 6....	256.1	10.9	0.290	0.196	0.040	0.236	86	+0.054
13....	255.0	6.5	0.173	0.169	0.033	0.202	81	—0.029

PERIOD 3, 35 DAYS.—GLUTENIN 16.4 PER CENT.

1910.								
June 20....	248.5	6.0	0.155	0.134	0.026	0.160	83	—0.005
27....	252.6	7.4	0.190	0.133	0.035	0.168	82	+0.022
July 4....	238.1	4.5	0.115	0.105	0.016	0.121	86	—0.006
11....	240.5	5.9	0.153	0.091	0.029	0.120	81	+0.033
18....	236.5	5.0	0.132	0.087	0.017	0.104	87	+0.028

PERIOD 4, 182 DAYS.—GLUTENIN 18 PER CENT.

1910.								
July 25....	241.0	6.6	0.174	0.129	0.022	0.151	87	+0.023
Aug. 1....	261.8	8.5	0.240	0.140	0.021	0.161	91	+0.079
8....	259.2	8.0	0.226	0.138	0.030	0.168	87	+0.058
15....	255.1	6.8	0.194	0.135	0.017	0.152	91	+0.042
22....	247.5	7.0	0.195	0.107	0.020	0.127	90	+0.068
29....	245.0	6.7	0.190	0.075	0.016	0.091	92	+0.099
Sept. 5....	241.5	7.5	0.212	0.132	0.030	0.162	86	+0.050
12....	235.2	6.3	0.179	0.171	0.014	0.185	92	—0.006
19....	244.8	9.3	0.263	0.209	0.040	0.249	85	+0.014
26....	240.0	8.3	0.237	0.191	0.019	0.210	92	+0.027
Oct. 3....	238.5	7.7	0.218	0.186	0.019	0.205	91	+0.013
10....	239.2	6.7	0.191	0.151	0.028	0.179	85	+0.012
17....	228.0	6.5	0.186	0.163	0.023	0.186	88	0.000
24....	223.5	6.9	0.198	0.162	0.037	0.199	81	—0.001
31....	238.7	9.4	0.269	0.202	0.037	0.239	86	+0.030
Nov. 7....	253.4	9.8	0.280	0.188	0.038	0.226	86	+0.054
14....	248.0	7.6	0.217	0.176	0.033	0.209	85	+0.008
21....	250.8	7.8	0.221	0.158	0.045	0.203	80	+0.018
28....	254.0	7.4	0.211	0.144	0.037	0.181	82	+0.030
Dec. 5....	253.6	7.9	0.226	0.174	0.039	0.213	83	+0.013
12....	254.0	9.0	0.252	0.208	0.040	0.248	84	+0.004
19....	262.5	11.0	0.301	0.214	0.064	0.278	79	+0.023
26....	....	10.8	0.296	0.220	0.052	0.272	82	+0.024
1911.								
Jan. 2....	279.8	11.7	0.321	0.222	0.049	0.271	85	+0.050
9....	273.5	8.7	0.237	0.208	0.035	0.243	85	—0.006
16....	275.5	11.5	0.317	0.270	0.038	0.308	88	+0.009

*In respect to the relatively high nitrogen balance compare last foot-note on page 7.
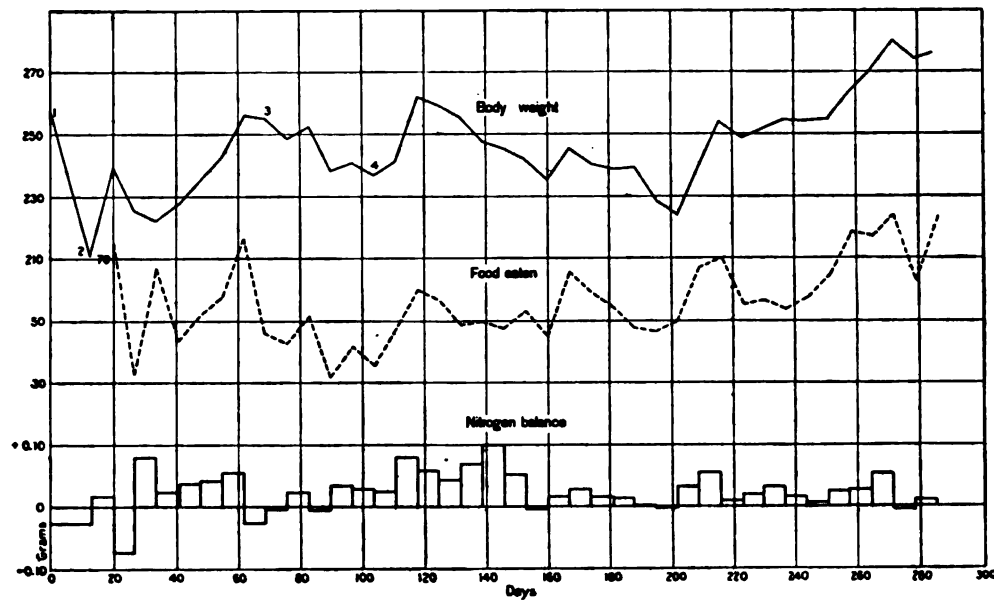
CHART XIX.—Rat 71 fed 286 days on Casein and Glutenin as the only proteins. See p. 48. Numbers on Body-weight line indicate time at which each period began.
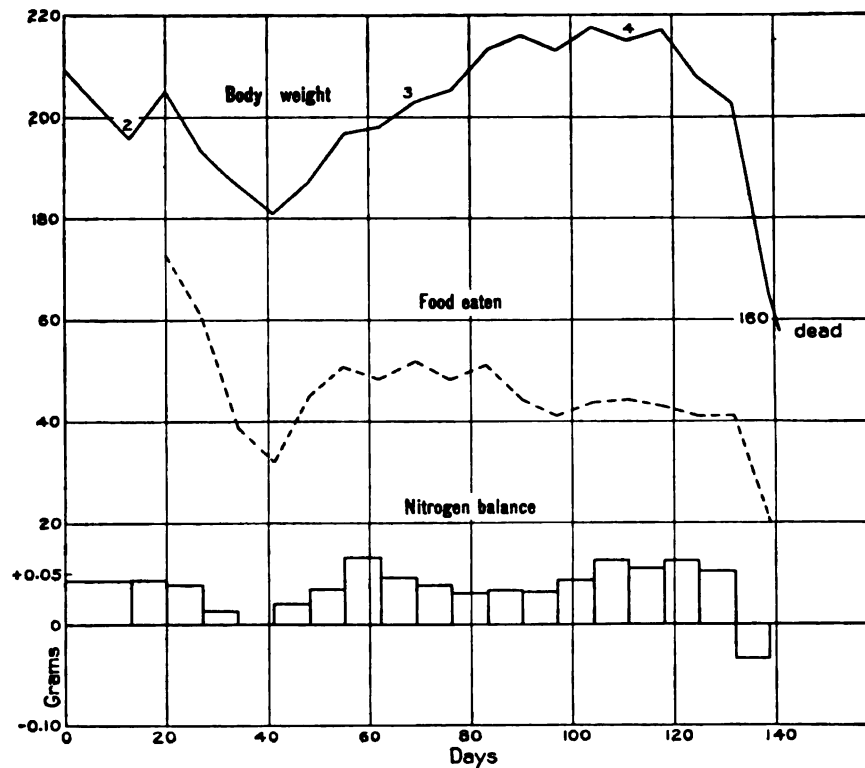

CHART XX.—Rat 72 fed 141 days on Casein and Glutenin as the only proteins. Numbers on Body-weight line indicate time at which each period began.

RAT 72.—This rat was fed with the same mixtures as those fed to rat 71 during the corresponding periods.

TABLE XXIX.—SUMMARY OF DATA ON RAT 72, FED FOR 141 DAYS ON MIXTURES CONTAINING CASEIN AND GLUTENIN AS THE ONLY PROTEINS.—DAILY AVERAGES.

PERIOD 1, 13 DAYS. CASEIN 12, GLUTENIN 6 PER CENT.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Apr. 5....	209.5							
18....	195.7	8.7	0.233	0.145	0.045	0.190	81	+0.043

PERIOD 2, 56 DAYS.—CASEIN 12 PER CENT, GLUTENIN 6 PER CENT.

1910.								
Apr. 25....	205.0	10.4	0.281	0.186	0.053	0.239	81	+0.042
May 2....	193.3	8.7	0.235	0.147	0.049	0.196	79	+0.039
9....	186.4	5.5	0.150	0.126	0.012	0.138	92	+0.012
16....	181.0	4.6	0.123	0.114	0.009	0.123	93	0.000
23....	187.2	6.4	0.170	0.126	0.024	0.150	86	+0.020
30....	196.4	7.2	0.192	0.120	0.038	0.158	80	+0.034
June 6....	198.0	6.9	0.214	0.123	0.025	0.148	88	+0.066
13....	202.8	7.4	0.196	0.131	0.019	0.150	90	+0.046

PERIOD 3, 42 DAYS.—GLUTENIN 16.4 PER CENT.

1910.								
June 20....	205.0	6.9	0.176	0.110	0.028	0.138	84	+0.038
27....	213.0	7.3	0.187	0.112	0.045	0.157	76	+0.030
Ju.y 4....	216.1	6.3	0.162	0.097	0.032	0.129	80	+0.033
11....	213.0	5.8	0.152	0.092	0.029	0.121	81	+0.031
18....	217.7	6.2	0.164	0.085	0.035	0.120	79	+0.044
25....	214.9	6.3	0.166	0.072	0.032	0.104	81	+0.062

PERIOD 4, 30 DAYS.—GLUTENIN 18 PER CENT.

1910.								
Aug. 1....	217.3	6.1	0.170	0.090	0.025	0.115	85	+0.055
8....	207.7	5.8	0.165	0.078	0.025	0.103	85	+0.062
15....	202.5	5.9	0.166	0.099	0.016	0.115	90	+0.051
22....	165.0	2.9	0.081	0.079	0.037	0.116	54	−0.035
24....	157.5							
Dead								

RAT 73.—This rat was fed during Period 1 on a mixture containing casein 12, zein 6, sugar 15, starch 29.5, lard 30, agar 5, salt mixture I 2.5 per cent, and nitrogen 2.38 per cent. In order to secure good utilization of the zein it was necessary to hydrate it by incorporating in the food 10 cc. of water per 100 grams of the mixture. The nitrogen content of the different batches therefore varied from 2.30 to 2.48 per cent. The actual nitrogen content of each batch fed was used in calculating the nitrogen balance which is given in table XXX. During Period 2, the diet contained pea legumin 18,

sugar 15, starch 29.5, lard 30, agar 5, salt mixture I 2.5, and nitrogen 2.97 per cent.

TABLE XXX.—SUMMARY OF DATA ON RAT 73, FED FOR 181 DAYS ON A MIXTURE CONTAINING CASEIN AND ZEIN AS THE ONLY PROTEINS AND FOR 53 DAYS ON ONE CONTAINING PEA LEGUMIN AS THE SOLE PROTEIN.—DAILY AVERAGES.

PERIOD 1, 181 DAYS.   CASEIN 12 PER CENT, ZEIN 6 PER CENT.

Date of experiment.	Body-weight.	Intake.		Nitrogen output.			N-utilization.	N-balance.
		Food.	Nitrogen.	Urine.	Fæces.	Total.		
1910.	gm.	gm.	gm.	gm.	gm.	gm.	p. ct.	gm.
Apr. 5....	179.0	.....	.....	.....	.....	.....	.....	.....
11....	174.0	3.9	0.092	0.177	0.024	0.201	74	—0.109
18....	165.0	7.5	0.177	0.171	0.018	0.189	90	—0.012
25....	167.0	8.0	0.189	0.163	0.013	0.176	93	+0.013
May 2....	156.0	5.9	0.143	0.147	0.013	0.160	91	—0.017
9....	140.0	4.0	0.098	0.123	0.008	0.131	92	—0.033
16....	127.8	3.2	0.080	0.107	0.009	0.116	89	—0.036
23....	137.4	5.2	0.123	0.111	0.006	0.117	95	+0.006
30....	126.1	3.1	0.072	0.084	0.007	0.091	90	—0.019
June 6....	126.5	4.4	0.102	0.108	0.005	0.113	95	—0.011
13....	129.5	4.8	0.112	0.091	0.008	0.099	93	+0.013
20....	128.2	4.0	0.094	0.084	0.006	0.090	94	+0.004
27....	128.7	3.7	0.086	0.075	0.004	0.079	95	+0.007
July 4....	123.3	3.4	0.080	0.081	0.006	0.087	92	—0.007
11....	123.3	3.9	0.093	0.080	0.007	0.087	92	+0.006
18....	125.0	3.7	0.088	0.064	0.007	0.071	92	+0.017
25....	118.3	3.6	0.084	0.076	0.005	0.081	94	+0.003
Aug. 1....	119.8	4.1	0.094	0.063	0.006	0.069	94	+0.025
8....	124.9	4.9	0.112	0.075	0.005	0.080	96	+0.032
15....	127.5	5.0	0.133	0.092	0.009	0.101	93	+0.032
22....	132.3	2.8	0.070	0.105	0.012	0.117	83	—0.047
29....	135.2	8.1	0.200	0.082	0.011	0.093	94	+0.107
Sept. 5....	131.5	5.4	0.134	0.096	0.011	0.107	92	+0.027
12....	132.5	5.1	0.126	0.110	0.007	0.117	94	+0.009
19....	138.2	6.1	0.151	0.128	0.014	0.142	91	+0.009
26....	142.8	7.1	0.170	0.139	0.017	0.156	90	+0.014
Oct. 3....	143.6	7.1	0.167	0.144	0.015	0.159	91	+0.008

PERIOD 2, 53 DAYS.—PEA LEGUMIN 18 PER CENT.

1910.								
Oct. 10....	136.3	5.2	0.153	0.168	0.036	0.204	76	—0.051
17....	127.5	5.1	0.150	0.165	0.020	0.185	87	—0.035
24....	121.1	4.6	0.136	0.142	0.018	0.160	87	—0.024
31....	110.7	4.3	0.129	0.133	0.023	0.156	82	—0.027
Nov. 7....	107.2	4.6	0.135	0.132	0.019	0.151	86	—0.016
14....	99.0	3.9	0.115	0.121	0.012	0.133	90	—0.018
21....	97.5	4.1	0.121	0.118	0.011	0.129	91	—0.008
29....	70.0							

These observations have thus shown the sufficiency of the artificial dietaries to maintain full-grown small animals for long periods of time (from 50 to 286 days) in nutritive equilibrium. In many experiments, such as Nos. 11, 14, 16, and 72, here reported, the animals died rather suddenly, without any previous period of notable
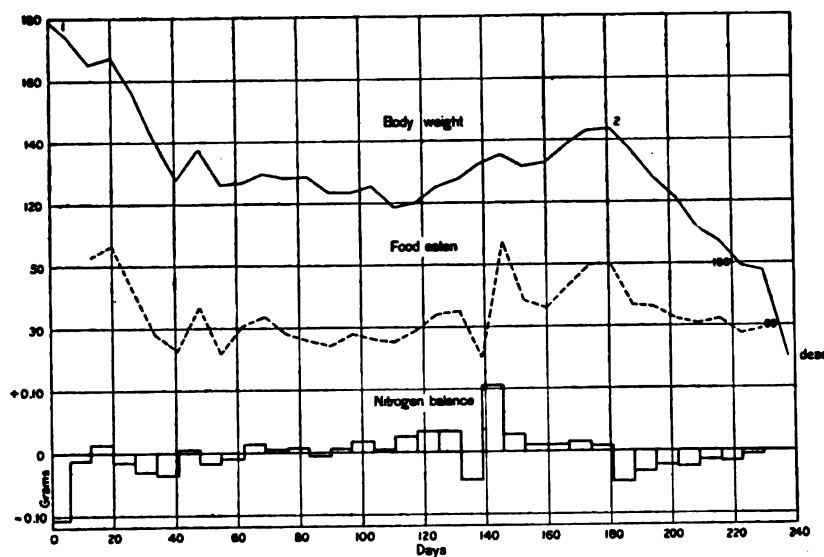
CHART XXI.—Rat 73 fed 181 days on Casein and Zein, and for 53 days on Pea-Legumin as the only proteins. See p. 50. Numbers on Body-weight line indicate time at which each period began.

decline sufficient to explain their ultimate death. This fact strongly suggests that death was not necessarily attributable to any primary nutritive defect, but rather to incidental causes. Occasional fatalities will not surprise those who have experienced the difficulty of protecting a large number of rats, under the conditions noted, from the appearance of infectious or parasitic maladies which may become fatal. In the same surroundings sudden death has also come to not a few of our animals on ordinary mixed diets consisting of seeds and vegetables. In some cases obvious causes were revealed at autopsy; but systematic post-mortem examinations have not been attempted.

With young rats fed similarly we have succeeded in maintaining weight, although with little if any growth. In our preliminary studies of growing animals the food intake was not determined with appropriate care to correlate our findings with the altered curves of growth; hence the insufficient diet rather than any chemical deficiency may have been a possible cause of arrested development. Rats of 30 grams initial weight have been kept by us for many days without gaining weight when fed with a mixture containing a single protein; with desiccated milk in the food they subsequently attained a perfectly normal growth.

Despite the obstacles encountered we are inspired to the belief that with modifications in the feeding suggested by our first year's experiments still further progress can be made. Meanwhile further conclusions respecting the inadequacy of the individual proteins for nutritive functions are not justified.

SUMMARY.

The problems of nutrition have been reviewed in this paper in the light of the newer knowledge of the chemical structure of the proteins. The possibilities of protein synthesis in animals and the conditions which this postulates; the significance of the availibility, palatability, and physical texture of the food-intake; the suggested role of various accessories—inorganic salts, lipoids, etc.; the distinction between the nutritive demands during the period of growth and those of later adult life, are brought within the range of discussion. The literature on experiments in which isolated food-substances have been fed to animals is discussed in some detail, with a critical consideration of some of the essential conditions of investigation which are demanded in successful research in this direction.

The methods of metabolism study with white rats used in this research are described and illustrated. Control feeding trials showed that the animals can be maintained in nutritive equilibrium and health for periods of many months under the conditions of experiment adopted. The failure to eat sufficient food is indicated as a cause for the unsuccessful termination of numerous experiments. The facts presented exclude the probability that monotony of diet is an insurmountable obstacle to nutritive success.

Numerous experiments are reported in which casein formed the sole nitrogenous constituent of the dietary. In this connection it is shown that the make-up of the inorganic constituents of the diet exercises an influential effect on the nutritive efficiency of the dietary. From the experience thus gained a "basal" ration was constructed on which rats were kept many months in good health. Some of these experiments in which the animals exhibited no noteworthy alterations in weight and showed a good gain in nitrogen are, as far as the authors are aware, the most successful recorded attempts at artificial nutrition with a constant mixture of pure food-stuffs, containing only a single protein. Satisfactory experience also followed the gradual complete substitution of the casein by other proteins, one animal continuing more than 217 days on a diet in which the sole protein was glutenin.

With young rats it has been possible to maintain weight with dietaries like those just mentioned, although with little if any growth. The limitations of the method are discussed and plans for continued investigation indicated.

JANUARY 1911.

FEEDING EXPERIMENTS WITH ISOLATED FOOD-SUBSTANCES.

BY

THOMAS B. OSBORNE and LAFAYETTE B. MENDEL,

With the Co-operation of EDNA L. FERRY.

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FEEDING EXPERIMENTS WITH ISOLATED FOOD-SUBSTANCES.

PART II.

INTRODUCTION.

In Publication 156 of the Carnegie Institution of Washington* we have discussed some of the problems of nutrition which have been raised by the newer investigations in the field of protein chemistry. The literature bearing on the feeding of isolated proteins was there reviewed in some detail, together with critical considerations of previously available experimental data. We described a plan for the study of metabolism and illustrated a method of investigation in which white rats were the experimental animals. For the details involved, our earlier paper must be consulted. A few protocols were there presented to show that the outlined mode of investigation offered a promising means for attacking certain questions in the field of nutrition.

INFLUENCE OF VARIOUS CONDITIONS ON NUTRITION OF WHITE RATS.

Numerous contingencies may arise to modify or vitiate the results of experiments in which animals are kept in cages and fed upon artificially prepared mixtures of isolated food-stuffs, quite independent of the factors inherent in the food-stuffs themselves or the combinations in which they are exhibited. Among these possibilities, the *caging* itself, involving continued restraint and limited opportunity for exercise, suggests an unfavorable environment. This factor can at length be disposed of.

Donaldson has concluded, from the best data obtainable, that "the three-year-old white rat is very old, and is justly comparable to a man of 90 years."† Rats have been kept in our cages in apparent good health and without difficulty during periods of more than 14 months—a very considerable part of the span of life in these animals (cf. Charts XXIII, XXIX, XXX).

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*Feeding experiments with isolated food-substances, by Thomas B. Osborne and Lafayette B. Mendel, with the co-operation of Edna L. Ferry. 1911. Pp. 53.

†H. H. Donaldson: A comparison of the white rat with man in respect to the growth of the entire body. Boas Memorial Volume, New York, 1906, p. 6.

Monotony of diet has been urged as an obstacle to success where the same food mixtures are daily furnished without change over long periods of time. Very closely associated with this is the question of the *palatability* of the diet. The two factors need, however, to be distinguished. The palatability of the diet has, perhaps, been over-emphasized in recent years in its bearing on the real nutritive value of foods. It applies primarily to the individual with highly organized nervous system and psychical functions. The quality found in foods which are unpalatable because they disgust or nauseate is something positive; the negative property of lack of palatability, *i. e.*, absence of stimulating taste, etc., is not necessarily a serious obstacle. In any event the palatability of the diet is difficult to determine or regulate and in attempting to control it experimentally in animals physiologists have been guided very largely by anthropomorphistic considerations.

We have now gathered observations which lead us to dismiss the idea that monotony *per se* leads to anorexia or other forms of nutritive failure in our animals, despite the comment which this feature has received from other investigators. There is no convincing reason why a continued unvaried diet should necessarily be unphysiological; one need only recall the fact that the diet of all sucklings is the same from day to day, and that many of the domestic animals are satisfactorily maintained on rations which are scarcely altered in qualitative make-up except at long intervals. We have observed rats in the same cage for considerably more than a year, during which the daily diet was invariably furnished in the form of our food-pastes. In some of these the composition of the paste was practically the *same* during these very long periods (cf. Charts XXVII, XXVIII, XXIX, XXX). It is true that we could point to many failures to maintain rats on an unchanged diet continued over much shorter periods. One must not, however, here confuse monotony with the real cause of decline. In these latter cases some deficiency or defect in the monotonous feeding sooner or later brings on a physiological state where anorexia occurs; and the advantage which a change of diet initiates ought primarily to be ascribed to the alteration in the food ingredients rather than the relief from the sameness of the intake.

Among factors referring more directly to the nature of the food itself, the *physical texture* and *digestibility* of the nutrients must be taken into consideration. The structure of the food materials may, under ordinary conditions of diet, influence its utilization in no small degree; and the low "coefficients of digestibility" shown by many foods of plant origin testify to this fact. In our experiments the products fed were isolated and reduced to a state of very fine comminution. At most, therefore, some inherent indigestibility of the individual foodstuffs employed might be concerned. Experiments

by M. S. Fine,* while they do not completely do away with this possibility, make it more evident than before that incomplete digestion is, in the case of plant products, for the most part associated with the peculiar vegetable tissues therein contained, rather than a specific resistance of the isolated nutrients.

The need of "*roughage*" to facilitate the normal evacuation of the gut has also been debated. We have, as a general procedure, added the indigestible polysaccharide carbohydrate agar-agar to food-pastes in order to approximate more nearly the conditions which prevail where cellulose enters into the mixed dietary. It can not be maintained, however, that this is necessary for satisfactory nutrition; for we have maintained animals over a year on foods (cf. Chart XXIX) devoid of indigestible principles, if perhaps an exception be made of some of the inorganic ingredients. It is well known that inorganic salts, notably bone ash, may exert the same influence as cellulose in giving bulk to the fæces; and they are often so employed in the technique of metabolism experiments at the present time.†

Aside from the proteins, in which our experimental interest has been primarily centered, our attention has been drawn more and more to those components of the diet which are not sources of energy, yet fundamentally indispensable—namely, the *inorganic compounds*. It is possible that further investigation will compel the inclusion of some of the more vaguely defined and unknown members of the groups spoken of as extractives, lipoids, etc., in this category. Every attempt made by us to approach the solution of the problem of inorganic salts in the dietary has brought fresh surprises.

When Forster‡ fed dogs and pigeons on salt-free foods he made the interesting observation that the animals speedily died—more rapidly even than when all food was withheld. He concluded:

Der im Uebrigen in Stickstoffgleichgewicht sich befindende thierische Organismus bedarf zu seiner Erhaltung der Zufuhr gewissen Salze; sinkt die Zufuhr unter einer gewisse Grenze oder wird sie gänzlich aufgehoben, so gibt der Körper Salze ab und geht daran zu Grunde.

The classic experiments of Lunin§ on mice led to a somewhat different interpretation of the need of salts. He showed that the animals survived longer on a diet containing an addition of sodium carbonate to the ash-free food than when sodium chloride was added. In the latter case the duration of life corresponded approximately with that observed on a salt-free dietary. From these facts it was argued that the foremost value of the sodium lies in its capacity to neutralize the acids (sulphuric, phosphoric) formed in the metabolism

*M. S. Fine: Dissertation, Yale University, 1911 (unpublished). Cf. Mendel and Fine: Journal of Biological Chemistry, 1911, vols. x and xi.
†Cf. Lothrop: American Journal of Physiology, 1909, xxiv, p. 297.
‡Forster: Zeitschrift für Biologie, 1873, ix, pp. 297-380.
§Lunin: Zeitschrift für physiologische Chemie, 1881, v, p. 31.

of proteins. Sodium chloride obviously has no potential neutralizing power. If the usefulness of the salts were associated solely with their specific character as salts, the salts of sodium ought to be somewhat comparably efficient.

The *function of the inorganic salts* is by no means exhausted, however, by the simple action of chemical equilibrium. It would lead us too far afield in this place to discuss the problem in detail. Charts XI, XII, and XIII, Part I, pp. 38–39) showing the marked differences induced by alterations in the inorganic salts of the diet, the other food components remaining unchanged, are highly suggestive. We have since then made numerous attempts to improve upon the salt mixture empirically selected and prepared somewhat in imitation of the ash of milk. Rats were kept alive (while they steadily declined) 84 days on a food mixture which analysis showed to contain only minimal, inevitable traces of ash (0.16 per cent, a considerable part of which was phosphoric acid derived from the casein). Chlorides were entirely lacking, distilled water being furnished for drinking. In view of this it is necessary to proceed with extreme caution in drawing conclusions from observations extending over brief periods. We shall refer to the subject again, it being sufficient here to emphasize the subtle and specific value of the salts. The lack of knowledge in this field has furnished an obstacle which we have only lately succeeded in overcoming in part.

Even when all these varied conditions are taken into account, there still remain, as we have pointed out before, *extraneous incidents* and *accidental factors* apart from nutrition itself, which may complicate or vitiate experiments like those projected. Disease, old age, injury, may be mentioned in illustration. Failures to maintain nutrition successfully under such extreme conditions do not necessarily imply a deficiency or inadequacy of the dietary. Accordingly, successful experiments must be given far greater weight than failures, where so many possibilities of detrimental influences, aside from the diet itself, are liable to arise over prolonged periods of observation. Some of the uncertainties have been eliminated by the experience previously gained. For example, the intercurrent diseases of our animals have been almost entirely excluded by the use of rats raised in the laboratory for this research. By the prompt elimination of diseased animals, by scrupulous attention to the conditions of the cages and feeding arrangements—in other words, by painstaking attention to hygienic factors—we have succeeded in maintaining a large number of animals in exceptionally good health, so that they have become the more suitable to permit of accurate conclusions regarding the effects of the diets studied. Furthermore, the age and hereditary factors in our animals are now known to us, so that another source of uncertainty has disappeared.

EARLIER EXPERIENCES OF THE AUTHORS.

As the result of the first year's experiments, it was found possible to maintain rats in health and apparent nutritive equilibrium over considerable periods of time on a mixture of isolated food-substances containing isolated proteins as the source of nitrogenous intake. For example, one protocol (Chart XXX) shows that a full-grown rat* was maintained satisfactorily in this way for more than 217 days on glutenin, the animal continuing on this régime at the time when the earlier report was prepared for publication. Rats were likewise maintained on diets in which other proteins, notably casein alone or in combination with isolated vegetable proteins, formed the sole nitrogenous food component, over periods of time exceeding any previously reported, at least under conditions in which the "purity" of the dietary substances was carefully maintained unchanged over equally long periods of time. By maintenance we do not merely mean that the animals remain alive. No feeding experiment is to be regarded as successful in fulfilling the nutritive requirements unless the animals approximately maintain their weight and health (or make normal growth if they are at a stage where this is still to be expected).

Although these apparently successful experiments indicated that the combinations of isolated food-stuffs employed satisfied the nutritive requirements of the rats and consequently constituted a complete food for the maintenance of mature animals, a prolongation of the observations has led to a less favorable outcome. A continuation of the experiments over longer periods has shown that in every case, sooner or later, the animal declined; and unless a change in the diet was now instituted within a comparatively short time the animals died. The Charts XIV, XV, XVI in our earlier paper illustrate this very well. The rats 23, 24, 25 were maintained without noteworthy alterations in weight over 130 to 160 days on a constant mixture including a single protein. The animals ate well, as the food records show, until the final period of decline.

These records can be duplicated, especially in respect to the decline, by many others, as for example Charts XLI, XLII, LXXVIII, LXXIX, LXXX, CII, CXV, CXVI appended to this report. The history of rat 71 is particularly instructive on this point.† This animal (see Chart XXX), weighing 257 grams on April 5, 1910, was put upon a diet containing casein (12 per cent) and glutenin (6 per cent) as the only proteins. Subsequently glutenin alone (16.4 per cent after 69 days and 18 per cent after 104 days) formed the protein of the diet. The rat continued in excellent nutritive

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*The earlier data regarding this animal, rat 71, are given in Publication No. 156, Carnegie Institution of Washington, p. 47 ff.

†The earlier data will be found in Publication No. 156, Carnegie Institution of Washington, pp. 47–48.

condition, eating well and exhibiting favorable nitrogen balances, until the end of 9½ months, when a gradual decline was observed. When the animal, at the end of a total feeding period of 335 days (42 days after the onset of the decline) was reduced to 162.5 grams in weight and near death, an attempt was made to see whether the decline was due solely to improper food or to the onset of old age or disease. With mixed food realimentation took place at once and the rat regained its weight in a week. A resumption of the former glutenin food during 35 days gradually led to a second decline, which was promptly checked by a change in the diet involving only the non-protein components of the food mixture. Here, then, is a record of the feeding of a full-grown rat, with the exception of 7 days, during a period of 454 days on a diet of isolated food-stuffs and on a diet containing a single protein, glutenin, for 371 days. This observation is remarkable because of the exceptional duration of the experiment. It is apparent, therefore, that *as a maintenance diet our food lacked something other than protein and energy.*

It remains to be shown precisely what the lacking component of our earlier diets is, whether some organic constituent or a peculiar proportion of inorganic ingredients. In any event it is evident that our original artificial food mixtures are incapable of supporting life indefinitely. Aside from this, however, records like that of rat 71 living on glutenin as the sole source of protein (see Chart XXX), or rat 133 (Chart LXX) on edestin, in contrast with rats XI, XIV, 146, and 157 (Charts CXXVI, CXXVII, CXXVIII, and CXXIX) on zein indicate the possibility of nutritive inequalities among the proteins themselves. Marked deficiencies tend to manifest themselves in comparatively short periods of time. In all of these cases the food actually consumed supplied sufficient *energy* for the immediate needs of the rats under investigation.

In the continuation of our experiments we have tried to profit by the first year's experiences. The methods have not been materially altered, except that the determination of the *nitrogen balance* has been omitted for the present. We learned from very numerous trials that it runs parallel with gain or loss of weight, and that the food intake varies closely with the weight of the animal, thereby making a record of the nitrogen unnecessary for judging the nutritive status of the rats employed. The same cages as heretofore have continued to prove very satisfactory. Instead of being rested on glass funnels for the collection of urine, they are now placed over a frequently changed sheet of absorbent paper (paper napkin) upon an enameled tray or pan. The fluid excreta thus promptly absorbed are frequently removed. It has already been pointed out that the food mixtures, prepared in paste form to prevent scattering by the animals and make it possible to obtain accurate records of the quantities eaten,

are not ideal in composition. The inclusion of 20 to 45 per cent of fat in the diet—a condition necessitated by the requirements of the experiments as outlined—seems like an excessive amount; nevertheless the utilization appears to be satisfactory and attempts to devise less objectionable modes of feeding have been unsuccessful in our hands.

ALIMENTARY BACTERIA AND NUTRITION.

In the course of our later studies we have been forced to take cognizance of the possible rôle of the bacterial flora of the alimentary tract in relation to appropriate nutrition. The water-free, fat-rich food characteristic of our experimental dietaries is not, broadly speaking, a particularly favorable medium for the development of certain groups of bacteria. The food of our animals therefore probably introduces into the digestive tube of the experimental animals bacterial invaders somewhat different from those which normally inhabit the alimentary tract of rats living on a free mixed diet. It is quite conceivable, therefore, that the bacterial conditions may be altered markedly as a result of the restriction in the growth of certain groups or the facilitation of the development of still others in the alimentary tract under these changed and sustained conditions of altered diet.* It is well known, for example, that in higher animals the preponderance of acid-producing organisms—to use a single illustration—may lead to an inhibition of the growth of the putrefactive group.

Guided by such considerations and the observation that those rats that have been maintained for long periods on diets with isolated food-stuffs become koprophagists, we have initiated the plan of feeding small quantities of the fæces of rats living on ordinary mixed food to some of our experimental animals, particularly in cases where symptoms of nutritive decline had become manifest. In nearly every instance the occasional addition of a small amount of the fæces from a normally fed rat at once stopped the decline in weight of the experimental animals to which a single protein was being fed. The results in almost all of these cases have been sufficiently striking to warrant a further pursuit of this topic. In our experiments there appears to be an unmistakable favorable influence induced by the occasional addition to the dietary of normal fæces with their high bacterial content. It must not be overlooked that other components besides bacteria, notably inorganic salts and unknown compounds, are also furnished by this means; but the quantities involved have always been very small. Further investigation will be necessary and is already projected.

The procedure in the case of these fæces-feeding trials consisted in introducing small amounts (about 0.5 gm.) of air-dry excrement

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*Cf. Herter and Kendall: Journal of Biological Chemistry, 1910, VII, p. 203; Kendall: Journal of the American Medical Association, April 15, 1911.

of rats on mixed food into the cages twice a week. It is an interesting observation that when the rats kept on a mixture of isolated food-substances were offered a choice between their own fæces and those of rats on mixed diets, they invariably chose the fæces of the latter. In many cases we have noticed a marked improvement in the nutritive conditions of animals maintained on a single-protein dietary when other rats were introduced into their cages for breeding purposes. In view of the favorable influence exerted by feeding the fæces of rats living on mixed food, it is quite likely that the presence of the strangers in the cages furnished a suitable opportunity to obtain "normal" fæces. This may explain the favorable results noted, in contrast with the negative effects seen where several rats living on the same single-protein diet have been maintained in the same cage.

The extent of the influence exerted by what we have, in the absence of a better explanation, assumed to be bacterial influences, is illustrated in some of the appended charts, the periods at which the fæces feeding was begun being indicated. The favorable effects have not been confined to experiments with one protein, but are manifested with casein (see Charts XXXIX, XL, XLI, and XLII), with edestin (see Charts LXVI, LXVII, LXVIII, and LXIX), and with gliadin (see Charts CI, CII, and CIII). Two failures may likewise be recorded, viz, an ultimate one with casein (Chart XLI) and a complete one with edestin (Chart LXXVII) as the protein component. These were not due to incapacity of the animals to grow, since further alteration of diet brought marked improvement.

The influence of fæces feeding is especially striking in the case of the gliadin tests, since without the addition of the fæces it has been almost impossible to attain satisfactory nutritive condition with this protein plus the special non-protein components of the food here employed. It is instructive therefore to compare such failures (cf. Period 2, Charts CXV and CXVI) with Charts CI and CIII, in which fæces feeding was resorted to.

In four of the experiments with edestin-food alluded to and recorded on Charts LXVI, LXVII, LXVIII, and LXIX, fresh fæces were not actually introduced into the cages; but the improvement, and even growth, in these young rats is coincident with the opportunity afforded to obtain "normal" fæces when other rats were daily introduced into the cages for a few hours.

In Chart CII is seen the result of an attempt to determine whether the favorable influence of the fæces is actually of bacterial nature. Fæces were fed as in the comparable gliadin experiments (Charts CI and CIII); but they were previously sterilized by thrice repeated heating in an atmosphere of steam. The decline of the animal was not prevented to the same extent with sterilized as with normal fæces. Further trials are necessary in this direction; and our

experience, though limited, invites attention anew to the possible nutritive functions of bacteria in the alimentary tract. Some of the aspects of this problem are referred to in our earlier paper.*

NUTRITION AND GROWTH.

The criteria of adequate nutrition are quite different in the case of *growing* animals from those applying to adults of the same species. During the period of adolescence it is not sufficient to maintain a condition of nutritive equilibrium and constancy of form or body-weight. In this stage of an animal's existence there should be evidences of development, and *growth* should manifest itself in a change of size. The curve of growth, expressed in changes of body-weight, is remarkably constant and characteristic for each species under the ordinary conditions of nutrition and environment. The individual values may at times fluctuate about a mean; but in the majority of cases the excursions from the average are not extensive.

In Chart XXII are reproduced curves illustrating the average normal rate of growth of the white rat, both male and female. The statistics for two of the curves are taken from Donaldson,† whose observations we have repeatedly verified in their general features. A third curve on the same chart represents the results of our own observations on the growth of the female white rat, regarding which data are less abundant. It will be noted that the curves of growth for the two sexes do not completely coincide in type. After an age of 70 days, represented by a body-weight of about 100 grams, the rate of growth is somewhat slower in the female than in the male. Indeed, the females rarely attain the large weight and size exhibited by the normal adult males of the same age, even in the case of animals from the same litter. We gain the impression that our "breed" of rats may in general be somewhat smaller than those measured by Donaldson and his collaborators. At any rate, the data available for statistical purposes are not very extensive and the curves here presented must have only a provisional value until more numerous measurements are made. In connection with certain of our experiments it may be stated that "the effect of mating on the growth-curve for the males can probably be neglected."‡ In the case of females, the effect of the bearing of young is, according to Watson,§ "to render the mated rats slightly heavier than the unmated—some of the excessive weight being due to the larger amount of fat present in the mated animals." Two charts (XXIV, XXV) are appended

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*Carnegie Institution of Washington, Publication No. 156, p. 3.

†Donaldson: A comparison of the white rat with man in respect to the growth of the entire body. Boas Memorial Volume, New York, 1906.

‡Cf. Donaldson: *ibid*, p. 8.

§Watson: Journal of Comparative Neurology, 1905, XV, p. 523.

to illustrate the influence of the course of pregnancy on the growth-curve of female rats of different sizes.

Making allowance for these minor divergencies, the striking uniformity in the progress of development in an animal nevertheless is a specific racial characteristic, and gives to the *curve of growth* a unique value as an index of the conditions which determine it. Growth is affected by two factors: nutrition, and what Rubner has termed "Wachstumstrieb" or growth-impulse. The latter factor is inherent in the animal. The limits are determined by heredity and can not be altered materially by the most abundant diet. "Eine noch so reichliche Ernährung vermag die in der Rasse und deren Vererbung gelegenen Grössen- und Massenbegrenzungen nicht zu mehren."[*]

We are not prepared, at this time, to discuss the nature of the hereditary factor or impelling "force" in growth.[†] Aron writes:

Die Natur des Wachstumstriebes ist dunkel. Sie ist eine Funktion der Zellen, im besonderen der jugendlichen Zellen. Welche Faktoren diesen Zelltrieb regulieren, wissen wir nicht, vor allem nicht, warum er allmählich aufhört. Ob hier die Zeitdauer seiner Wirksamkeit, ob die erreichte Grösse des Individuums den Ausschlag für das Abklingen des Wachstumstriebes gibt, ist bis jetzt nicht entschieden.[‡]

Rubner has attempted to formulate its character:

Die eine grosse Unbekannte auf dem Gebiete der Wachstumsphysiologie ist der *Wachstumstrieb*, der in gesetzmässiger Weise den Gang der Entwicklung, Massenzunahme, durch die Regelung der Ernährung leitet. Den *Urgrund* hat dieser Wachstumstrieb in der Geschwindigkeit der Kernteilung; wie wir noch sehen werden leitet sich hieraus der ganze Prozess des Stoffumsatzes ab. Die Kernteilungsgeschwindigkeit ist offenbar etwas der Spezies Eigentümliches, somit sind wir nicht in der Lage, vorläufig tiefer in dieses Problem vorzudringen.[§]

The second factor in growth, namely, *nutrition*, can be approached more easily by the experimental method. It is along this line that we have hoped, therefore, to be able to attack some of the problems of the relative value of the individual foodstuffs. It is well known that growth can be retarded by means involving the nutrition of the individual. Waters has well summarized the situation in these words:

The upper limit of the size of an animal is determined by heredity. The stature to which an animal may actually attain, within this definitely fixed limit, is directly related to the way in which it is nourished during its growing period. Some of our approved theories have been so extreme as to hold, in effect, that the animal must grow at its maximum rate practically every

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[*]Rubner: Archiv für Hygiene, 1908, LXVI, p. 82.
[†]Certain aspects are considered in C. S. Minot: The problem of age, growth, and death. New York, 1908.
[‡]Aron: Biochemische Zeitschrift, 1910, xxxp. 207.
[§]Rubner: Archiv für Hygiene, 1908, LXVI, p., 86.

day from birth to complete maturity in order to reach its normal size, or the full stature fixed by heredity. In other words, it is assumed that the animal has but one way of reaching its full stature and full development, viz., by developing to its upper limit through its entire growth period. This assumes that the organism is utterly incapable of compensating for any retarded development at any time in its growth period, either by a subsequently increased rate of growth, or by extending, even in the slightest degree, the growth cycle, much less by growing for a time at least when so sparsely fed that no gain in weight occurs.*

Rubner has expressed the rôle of nutrition in growth as follows:

Kann die Ernährung auch keinen Wachstumstrieb schaffen, so kann sie, wenn ungünstig und unzweckmässig, doch zu einem *Hemmnis* des natürlichen Wachstums werden. Wachstumsbehinderung ist innerhalb gewisser Grenzen noch keine Ursache einer Existenzgefährdung, ein Kind, dem die Nahrung normales Wachstum hindert, stirbt deswegen durchaus nicht, es holt später leicht wieder ein, was es versäumt hat . . . Nur das steht sicher, dass die Behinderung des Wachstumstriebes, wie dies wirklich vorkommt, nicht während der ganzen Wachstumsperiode andauern darf, da sonst allerdings die Grösse des Individuums dauernd Schaden leidet. Verlorene Körpergrösse in der Jugendzeit kann nach Vollendung der Wachstumsperiode nimmermehr abgeglichen werden . . . Eine *optimale* Ernährung, wie die *Wachstumsernährung* sein muss, stellt an die richtige Auswahl der Stoffe ganz andere Anforderungen als eine einfache Erhaltungsdiät.†

Obviously the energy problem plays an important part in the nutrition of growing animals. For the present we are primarily concerned with the qualitative aspects of the diet rather than the quantitative features of the food-intake. These two factors may at times stand in intimate relation to each other; improperly constituted food may, for example, modify the amount eaten and therefore the energy available for growth. As was intimated in our first report we have been able to arrest development in rats by feeding mixtures containing a single protein; but inasmuch as the food intake was not measured at that time, it was impossible to say whether the chemical character of the diet or a quantitatively inadequate food consumption was responsible for the dwarfing. The *fact* brought out was that in these young animals there could be a *maintenance of weight*, precisely as in older rats.

Waters has appropriately emphasized the necessity of a more exact definition of what is meant by *maintenance*, in contrast with growth. He writes:

It has long been assumed that the body of an animal, when supplied with only sufficient nutriment to maintain its weight, remains constant in composition and that no growth or production or change of any sort occurs.

*H. J. Waters: The capacity of animals to grow under adverse conditions. Proceedings Society for the Promotion of Agricultural Science, 1908, XXIX, p. 3.
†Rubner: Archiv für Hygiene, 1908, LXVI, pp. 82–83.

It is true that the term *maintenance* has been used somewhat loosely, but in general we have been in the habit of regarding the animal in maintenance when its live weight was constant. A more correct definition of the term would perhaps be to say that the animal was in maintenance when its body was in energy balance, but the live weight has been the conventional measure of our maintenance values.*

It is generally admitted that the proteins satisfy several functions in a growing organism as well as in the adult. The first is that of maintenance, corresponding with what has been termed the "Abnutzungsquote," or wear-and-tear, by Rubner. This makes good the inevitable losses occasioned by the processes of metabolism, cellular and secretory processes, etc. It is a small yet ever present need for protein (as well as energy), representing in a general way the minimal protein need of the stationary organism. Any excess of protein beyond this maintenance requirement may, in the adult, experience temporary storage ("Ansatz") or be devoted to dynamogenic purposes; but in the organism capable of development it contributes a share toward growth. It should be emphasized that the rate of growth is not by any means proportional to the excess of protein available. It is surprising, indeed, how small a content of protein in the dietary suffices to make growth possible. Rubner and Heubner† found, for example, that in suckling infants a protein intake equivalent to 5 per cent of the total calories satisfies the protein needs of maintenance, while 7 per cent permits of growth. Rubner writes:

Das Wachstum ist eine *Funktion der Zelle*, es kann durch unzureichender Eiweisszufuhr *latent* werden, aber Eiweiss vermag *nicht* die Wachstumsschnelligkeit über die von der Natur gestreckten Grenzen zu heben, daher wird mit steigender Eiweissmenge in der Kost prozentisch weniger verwertet und das überflüssig zugeführte Eiweiss wird einfach als Brennstoff verbraucht der isodyname Mengen N-freier Stoffe einspart. Diese starke Anziehung von Eiweiss zum Wachstum nimmt im Laufe der Entwicklung ab und ist am grössten in der ersten Zeit des Lebens.‡

Waters has found in his extensive studies on cattle that growth, in the sense of changes of size and form, may occur even under adverse nutritive conditions. Fundamentally such investigations touch upon the much controverted question as to the relative importance of breeding and feeding in determining the shape and activities of mature animals. It is well known that by limiting the food supply of an ungrown individual, its development may be retarded. If the underfeeding is prolonged through the cycle of growth, the full stature limited by heredity may not be reached.

*H. J. Waters: The capacity of animals to grow under adverse condition. Proceedings Society for the Promotion of Agricultural Science, 1908, XXIX, p. 3.
†Rubner and Heubner: Zeitschrift für experimentelle Pathologie, 1905, I, p. 1.
‡Rubner: Archiv für Hygiene, 1908, LXVI, p. 110.

Waters asked the question:

Will this animal of smaller stature be in the same proportion with respect to all the organs and the different parts of its body as though it had been nourished to its full capacity and had attained its normal size and maximum development? Or will in this period of sparse nourishment a more complete development occur in certain parts of the body than in other parts? In short, when there is not sufficient food supplied to the growing animal to develop all of the organs and all parts of the body to their full limit and extent, will the rate of development of certain of these organs or parts diminish earlier than others and will the development of certain parts cease altogether before the development of other parts is diminished in rate and is it possible that some parts may cease their development before that of other parts?*

In actual experiments at the Missouri Agricultural Experiment Station, Waters found that ungrown cattle may remain at a constant body-weight for a long period of time, and yet increase in height and apparently decrease their store of fat. In other words, the skeleton has grown, or at least the bones have lengthened. Two interesting illustrative protocols† are reprinted here, one, Table XXXI, in which a stationary body-weight was maintained, the other, Table XXXII, in which there was actual decline on a starvation ration.

TABLE XXXI (FROM WATERS, TABLE II).— SHOWING INCREASE IN HEIGHT AT WITHERS, LENGTH OF HEAD, DEPTH OF CHEST, WIDTH OF CHEST, AND LOSS OF FAT IN A YEARLING STEER WHEN KEPT AT A STATIONARY BODY-WEIGHT.

No. 595. Grade Hereford. Born May 15, 1907. Nine and a half months old when experiment began. Full fed four months previous to beginning of trial. Condition when put on maintenance, medium. Weight at beginning of trial, 609.2 lbs. Weight at close of trial, 595.6 lbs. Average of ten daily weights.

Date.	Height at withers.	Length of head.	Depth of chest.	Width of chest.	Condition.
1908.	cm.	cm.	cm.	cm.	
Feb. 8................	109	38	56	35	Medium.
Mar. 13................	112.5	40	58	36.5	Medium.
Apr. 11................	115.5	41	57.5	35.5	Medium to thin.
June 2................	116	42	59	33.5	Common.
July 1................	117.5	44	58.5	34	Common.
Aug. 1................	117.5	44	59	33	Common.
Sept. 2................	117.5	44	59.5	33	Common to fair.
Sept. 29................	119	45.50	59.5	33.5	Fair.
Oct. 30................	119.25	45.75	59.5	31	Fair.
Nov. 30................	119.5	45.75	59.5	31	Fair to thin.
1909.					
Jan 1................	119.75	46.50	60.5	30.75	Thin.
Jan. 30................	119.75	45.50	60.75	30.75	Thin.
Total height in 12 months.	10.75	7.50	4.75	*— 4.25	
Per cent gain...........	9.86	19.73	8.48	*—12.1	

NOTE.—When slaughtered, carcass was classed as poor canner. All visible subdermal and intramuscular fat had disappeared.
*—Denotes a loss.

*H. J. Waters: The influence of nutrition upon the animal form. Proceedings Society for the Promotion of Agricultural Science, 1909, XXX, p. 71.
†From H. J. Waters: The capacity of animals to grow under adverse condition. Proceedings Society for the Promotion of Agricultural Science, 1908, XXIX.

TABLE XXXII (FROM WATERS, TABLE VI).—SUB-MAINTENANCE.

Steer No. 591. Grade Hereford. Born May 15, 1907. Experiment began Feb. 26, 1908.
Age of animal at beginning of experiment, nine and a half months.
Full fed four months before trial began and was in good condition.
Weight at beginning of trial, 572.7 lbs. Weight at close of trial, 490.4 lbs.
Total loss in weight, 82.3 lbs. Average daily loss 0.43 lb.   —Denotes loss.

Date.	Height at withers.	Length of head.	Depth of chest.	Width of chest.
1908.	cm.	cm.	cm.	cm.
Feb. 8.............	110.5	39	57	38.5
Mar. 13.............	113	41.5	57.5	34.5
Mar. 28.............	115	42	....	35
Apr. 11.............	114.5	41	58	33
May 2.............	116	42	57	33
June 1.............	118.5	44	57.5	33
June 29.............	120	44	58	31.5
July 31.............	119	44.5	59.5	29.5
Aug. 31.............	119.5	44.5	58	29
Gain...............	9	5.5	1	— 9.5
Per cent...........	8.14	14.10	1.75	—24.6

The following is from Waters, in regard to a series of comparable cattle maintained by him on different nutritive planes, designated as sub-maintenance, maintenance, and super-maintenance:

It is to be observed that there is no appreciable difference in the rate of growth in height of these three animals on widely different nutritive planes, from the beginning of the experiment (February) to the end of June. At this time the curve of the sub-maintenance animal flattens perceptibly. A month later, the maintenance animal is apparently responding to the influence of the low nutritive plane. As would be expected, in the case of the super-maintenance animal, the rate of growth remains unchanged. It may be surprising to many [Waters writes elsewhere] that an animal on maintenance, much less on sub-maintenance, should show any increase whatever in the width of hip or length of leg . . . Apparently the animal organism is capable of drawing upon its reserve for the purposes of sustaining the growth process for a considerable time and to a considerable extent. Our experiments indicate that after the reserve is drawn upon to a considerable extent to support growth the process ceases, and there is no further increase in height or in length of bone. From this point on the animal's chief business is to be to sustain life. This law applies to animals on a stationary live weight as well as those being fed so that the live weight is steadily declining, and indeed to those whose ration, while above maintenance and causing a gain in live weight, is less than the normal growth rate of the individual. Such an animal will, while gaining in weight, become thinner, because it is drawing upon its reserve to supplement the ration in its effort to grow at a normal rate.*

More recently Aron† has made comparable studies on growing dogs. He formulated his problem in the following words:

"Was wird geschehen, wenn für kürzere oder längere Zeit in der Nahrung nur so viel Energie usw. zugeführt wird, wie erforderlich ist, um den Erhalt-

*H. J. Waters: How an animal grows. Kansas State Board of Agriculture, Seventeenth Biennial Report, 1909–1910, I, p. 208.
†Aron: Biochemische Zeitschrift, 1910, xxx, p. 207.

ungsbedarf des wachsenden Organismus zu befriedigen, aber kein Ueber-
schuss, der als Wachstumsenergie dienen könnte? Die nächstliegende
Annahme ist, dass dann kein Wachstum stattfindet, dass der Wachstums-
prozess stillsteht. Können wir nun wirklich den Wachstumstrieb durch
Nahrungsbeschränkung unterdrücken? Wie lange? Und was geschieht
später mit einem wachsenden Organismus, dessen Wachstum eine Zeitlang
hintan gehalten worden ist? (p. 208.)

Aron succeeded by restricted feeding in attaining constancy of
body-weight in practically all of his dogs, in some cases during a
period of nearly a year. The daily gains or losses fluctuated within
a few grams. The description of the animals during the experiments
is of interest to us:

Bei allen Hunden konnte man deutlich beobachten, wie die Tiere trotz
des Gewichtsstillstands *wuchsen*, d. h. an Höhe und Länge zunahmen.
Dabei wurden die Tiere zusehends magerer, Fett und Muskeln schienen an
Masse abzunehmen, die runden Formen schwanden, die Knochen traten
eckig unter der Haut hervor, und schliesslich schienen die Tiere nur noch
aus Haut und Knochen zu bestehen. Trotzdem waren die Hunde nicht
etwa schwach. Im Gegenteil, sie waren lebhaft, liefen und sprangen umher,
oft mehr als ihre normalen Brudertiere, die ein zwei- oder dreimal zo grosses
Körpergewicht zu bewältigen hatten. Dieser Zustand zunehmender
Abmagerung unter ständiger Grössen-, d.h. Längen- und Höhenzunahme
bei Konstantbleiben des Gewichtes dauerte je nach dem Grade der Nahrungs-
entziehung ǀungefähr 3 bis 5 Monate an. Wurde jetzt, wenn das Tier
völlig abgemagert war, . . ., die Nahrungsmenge *weiter so gering* belassen
wie vorher, so ging das Tier unter geringem Gewichtsverlust in völliger
Inanition zugrunde. Wurde aber jetzt die Nahrungsmenge etwas erhöht,
wie bei Hund A, so hielt sich das Tier zwar vollkommen abgemagert, aber
auf konstantem Gewicht. *Und jetzt erweist sich dieser Gewichtsstillstand als
identisch mit Wachstumsstillstand!* Der Hund A ist noch weitere 5 Monate
auf dem gleichen Gewicht gehalten worden, ohne dass sich nun in seinem
Aussehen nennenswerte Aenderungen konstatieren liessen.

Durch geeignete Nahrungsbeschränkung gelingt es also, wachsende
Hunde beliebig lange auf konstantem Gewicht zu halten. Natürlich darf
man nicht allzu junge Tiere nehmen. Während dieses Gewichtsstillstandes
gehen aber gewaltige Umwandlungen im Tierkörper vor, die sich äusserlich
in dem fortschreitenden Längen- und Höhenwachstum und der Abmagerung
dokumentieren.

Offenbar ist trotz des Gewichtsstillstandes das Skelett weiter gewachsen
und hat nicht nur an Grösse, sondern auch an Masse zugenommen. Folg-
lich müssen andere Körpergebilde (wie Haut, Fleisch, Organe usw.)
an Gewicht verloren haben; denn sonst könnte ja das Gewicht des Tieres
nicht das gleiche geblieben sein. Ebenso wie die Massenverhältnisse der
einzelnen Körpergebilde haben sich nun höchstwahrscheinlich auch die
Mengenverhältnisse der einzelnen Körperbestandteile, wie Fett, Eiweiss
usw., beträchtlich verschoben. (p. 212.)

Aron's analyses of the underfed dogs showing stationary weight
in comparison with well-fed control animals indicate that in addi-
tion to the bones, the brain also was protected from loss of weight,
while the adipose and muscular tissue suffered notable losses. Most
striking is the degree to which water has replaced the tissue substance

utilized to compensate for the lack in the food, the blood especially becoming distinctly "watery," as the selected protocol shows:*

TABLE XXXIII.—CONTENT OF DRY MATTER IN VARIOUS TISSUES.

	Control dog.	Underfed dog.
Blood	*18.8	*5.1
Brain	24.6	19.3
Bones	57.2	40.0
Muscle	29.1	15.2

*Protein = N×6¼.

It is apparent here, as in Waters's experiments, that the energy deficit has been furnished by the body. "Sind alle verfügbaren Reservestoffe aufgebraucht, dann gewinnt der Erhaltungstrieb die Oberhand über den Wachstumstrieb, und das 'Wachstum' stockt." (Aron, p. 222.)

In relation to our own later observations it is desirable to quote Aron's view regarding the impulse to growth. He concludes:

. . . dass die innere treibende Kraft zum Wachsen überhaupt in dem Kerngerüst des Körpers, dem Skelett, ruht. Die Muskulatur verfügt anscheinend über gar keinen richtigen Wachstumstrieb. Sie folgt dem wachsenden Skelett nur dann, wenn die Ernährungsverhältnisse es erlauben, vielleicht auf Grund rein mechanischer Kräfte (Zug).

Recht interessant scheint zum Schluss noch die Frage, wie sich bei den durch lange fortgesetzte Unterernährung im Wachstum zurückgehaltenen Tieren die Entwicklung und die Entwicklungsfähigkeit verhält. Mein Tiermaterial war nicht ausreichend, um ein Studium der Geschlechtsorgane der zwar im Alter der Geschlechtsreife stehenden, aber im Wachstum weit zurückgebliebenen Tiere zu gestatten. Dagegen scheint mir die Beobachtung der Stimme auf ein wirkliches Zurückbleiben der Entwicklung auf dem infantilen Stadium zu deuten. Die Unterschiede zwischen den Brudertieren der ersten, zweiten und vierten Versuchsreihe waren auffällig. Die im Gewicht zurückgebliebenen Tiere schrien kreischend wie junge Hunde, während ihre normalen Brudertiere mit tiefem Tonfall bellten. In ganz dem gleichen Sinne spricht die von Waters festgestellte Tatsache, dass seine in Gewicht und Wachstum zurückgebliebenen Tiere ein Fleisch, das für 'Kalbfleisch' charakteristisch war, aufwiesen, während sie dem Alter nach schon "Rindfleisch" besitzen sollten. (pp. 222–223.)

Studies of the relation of weight to the measurements of children during the first year† have also given evidence of "disproportionate" growth in the case of poorly nourished infants. Whereas there is, in the normal infant, a fairly constant relationship between body-weight and height, circumference of head, chest, etc., this is not true where proper increase of body-weight is retarded by poor nutrition. For example, in children whose weight at the end of the third month

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*Aron: Biochemische Zeitschrift, 1910, xxx, p. 220.
†E. C. Fleischner: Archives of Pediatrics, October 1906.

is only equal to that of a normal child at birth, the height has been found above that of the latter, illustrating, as Fleischner remarks, "that age plays some part in the growth of the infant, independent of the weight." This corresponds with the cases of the animals already cited. Fleischner concludes from his measurements of 500 children of whom 25 per cent were well nourished, 35 per cent fairly well nourished, and 40 per cent poorly nourished:

It is in the poorly nourished children that age plays its most important part . . . In the poorly nourished children, most of whom are probably somewhat premature, when the weight is below normal, all the measurements are correspondingly below normal. The height and circumference of the head reach the normal birth measurements a little ahead of the weight, while the chest and abdomen are two months later in reaching the measurements of a normal child at birth. When the weight is stationary the increase in the measurements is very small, depending upon the slight influence which age has upon the growth of the infant notwithstanding the weight. The measurements of infants of the same weight, notwithstanding the age, are very similar, the small difference depending, as when the weight of a child is stationary, upon the very slight influence of age upon growth. The final conclusion can be drawn that during the first year of life the primary factor in the increase of the measurements of the body is steady, consistent increase in the weight, the influence of age being secondary and much less important.*

SUSPENSION OF GROWTH ON A MAINTENANCE DIET.

Early in the course of our investigation we noted that young rats could remain in apparent good health while living on some of the mixtures of isolated food-stuffs, without giving any evidence of growth. In some instances the animals ultimately declined and died where the diet was not changed; but in numerous cases body-weight, which we used as our guide, remained practically unchanged or showed a minimal slow increase (cf. Charts XXXVII, LXIII, and LXIV). The experiment showing the greatest growth under these dietary conditions is recorded in Chart XXXVIII. Other investigators have met with this stationary condition and accepted it as evidence of satisfactory nutritive equilibrium. We soon became convinced, however, that a diet which will not induce real growth at the proper age is unquestionably defective from the standpoint of perfect nutrition. Furthermore, inasmuch as the ungrown rat has a far smaller reserve of available energy and manifests the utilization of a suitable diet both speedily and conspicuously by its measurable changes in size, the animal becomes an exceptionally appropriate subject at this early stage for the study of the nutritive requirement.

The most precise evidence which we can present at this time of the stationary condition of the animals which we have stunted by

*E. C. Fleischner: Archives of Pediatrics, October 1906.

the particular dietaries adopted is derived from measurements on three young rats of the same litter maintained for 124 days without noteworthy growth, on a diet of

	Per cent.
Glutenin	18.0
Starch	14.5 to 34.5
Sugar	15.0 to 20.0
Agar	5.0
Salt mixture I	2.5
Lard	20.0 to 45.0

The curves of growth of these animals as well as three others from the same brood fed on mixed food or the milk-food mixture (and showing a normal growth) are reproduced in Charts LXXXI, LXXXII, LXXXIII, LXXXIV, LXXXV, and LXXXVI.

The animals were killed at the age of 178 days and measurements were made by Dr. S. Hatai, of the Wistar Institute. The tabulated data are given on the following page, together with a report from Dr. Hatai, to whom, as well as to Dr. Donaldson, we are greatly indebted for helpful cooperation.

The statistics of body-length, weight of brain, spinal cord, etc., of the stunted animals at an age of 178 days are comparable with those characteristic for normally growing rats of the *same* body-weight, which is attained at an age of approximately 54 to 63 days. Here, then, are illustrations of maintenance without growth.

Dr. Hatai further reports as follows:

Since it seems to be the least variable character, I have selected the body-length as the basis for computation. When the other characters which we can measure are calculated from the formulas based on body-length, it is seen that the observed weight of the brain and of the spinal cord agrees closely with the calculated in both the control and the stunted rats. Thus both series have a growth of the nervous system normal to their body-length. In the control series, the percentage of water observed in both the brain and the spinal cord agrees with that calculated according to the body-length. In general then the control rats agree with the general population in these characters. Since the stunted rats have an abnormally small body-length for their age, they can not be treated by the formula for determining the percentage of water from body-length. When, however, we take the estimated percentage of water for 178 days (see Donaldson*) we find that this value agrees with that observed in the stunted series. It may be further noted that the ratio between body-length and tail-length is the same in both series. We therefore conclude that *in both series the body-weight is normal to the body-length; the brain and spinal cord weight normal to the body-length; and the percentage of water normal for age.* Concerning other organs we have no data, but we may infer from the foregoing that they also have weights normal to the body-length. You will see from the above that the stunted rats though small have the general relative development of the controls and that in the only case where it is possible to follow the maturing process, that is in the percentage of water in the nervous system, they have matured in accordance with their age (see Donaldson*).

*Donaldson: Journal of Comparative Neurology, April 1911.
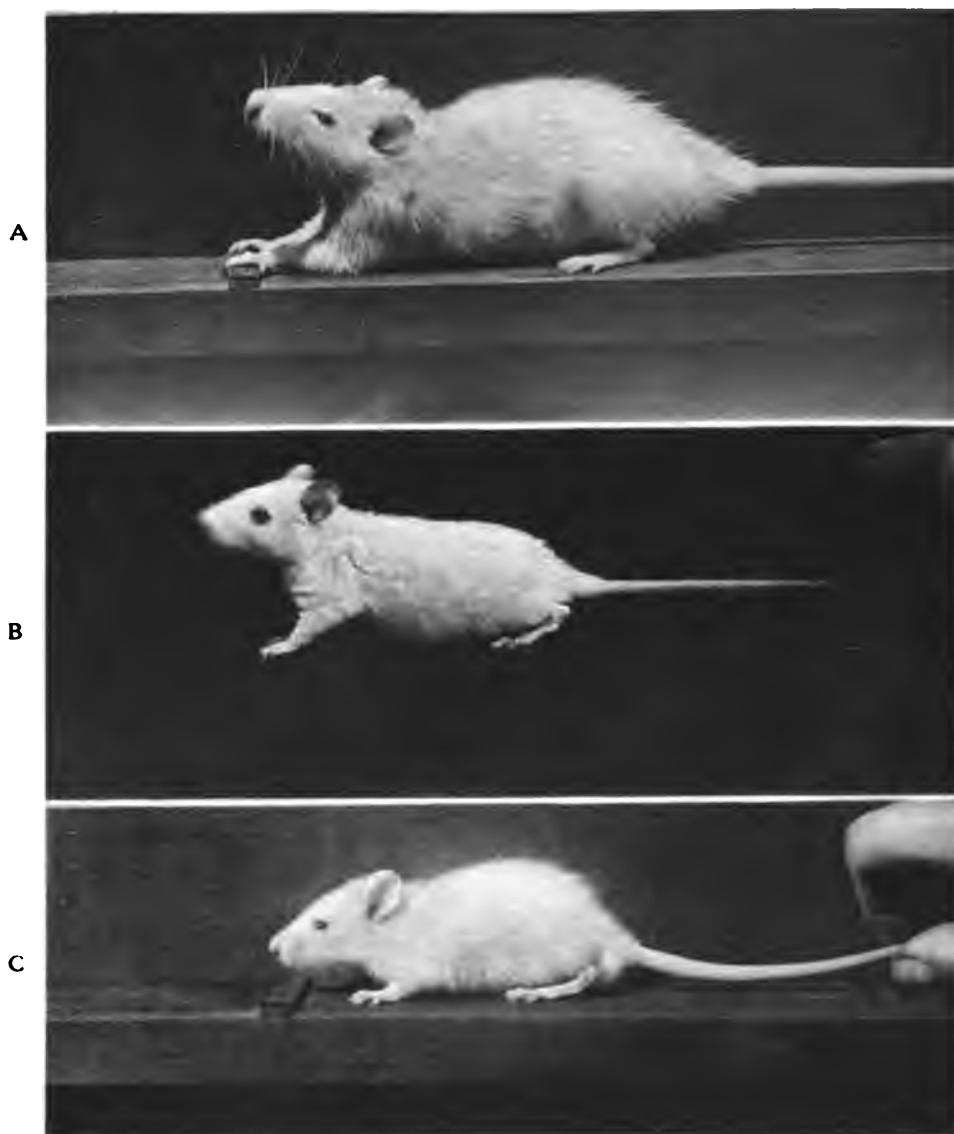
A. Rat 238, female.   Age 140 days, weight 144 grams, which is normal for a rat of same age as 240.

B. Rat 240, female.   Age 140 days, weight 55 grams.   Same brood as Rat 238.

C. Rat 305.   Age 36 days, weight 55 grams.   Showing the appearance of a normal rat of same size as 240.

A and B show the contrast between two rats of the same age, one of which (Rat 240) has been stunted.
    The lower two pictures afford a comparison between two rats of the same weight, but widely differing in
    age.   The older, stunted rat, B, has not lost the characteristic proportions of the younger animal, C.
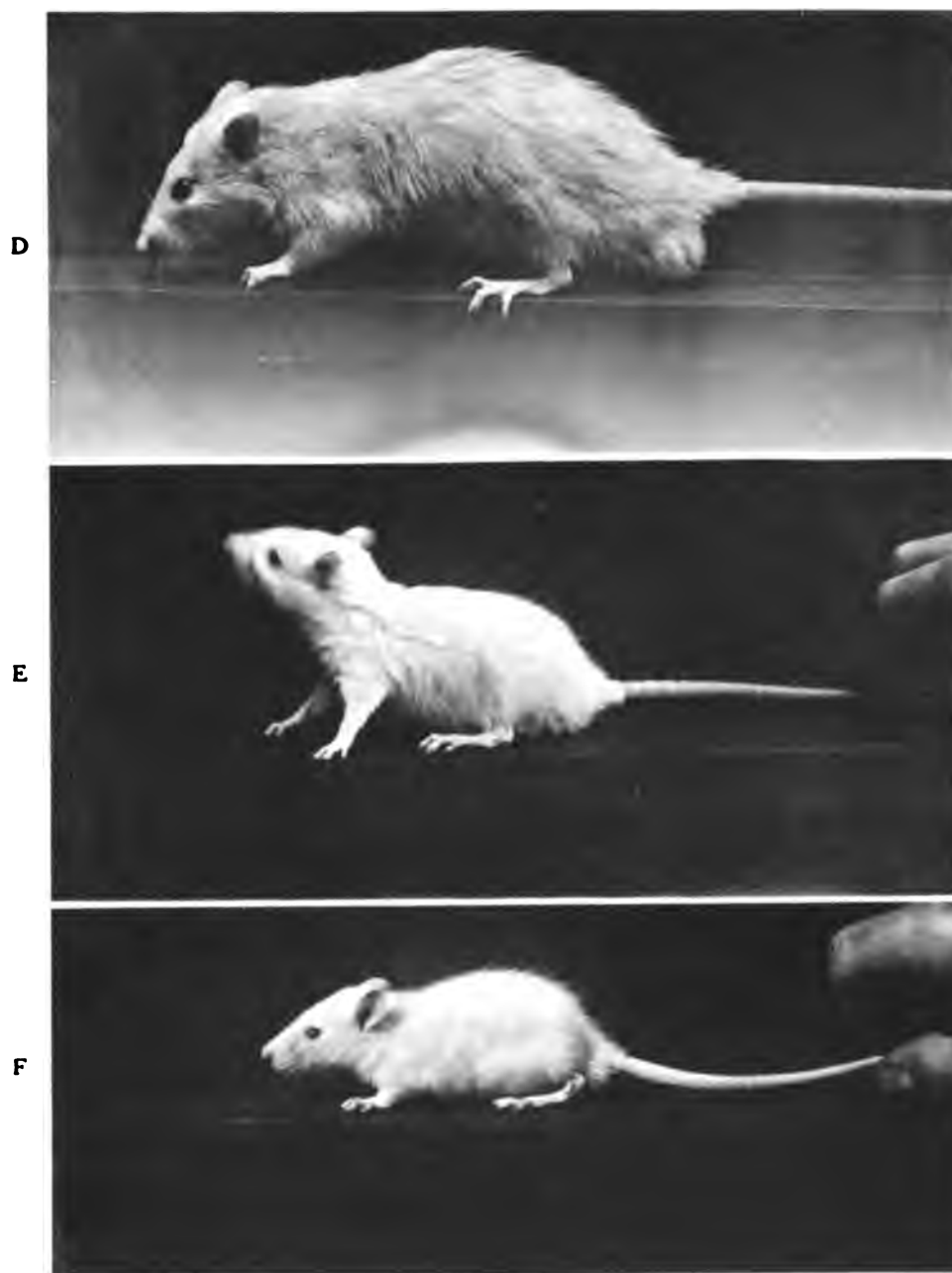
D. Rat 168, male. Weight 235 grams, which is normal for a rat of the age of 220 shown below.

E. Rat 220, male. Age 148 days, weight 58 grams.

F. Rat 305. Age 36 days, weight 55 grams. Showing appearance of a normal rat of same weight as 220.

D and E show the contrast between two rats of the same age, one of which (Rat 220) has been stunted. The stunted rat is not essentially altered in its bodily proportions from those of a much younger rat of the same weight.

Table XXXIV.—Hatai's Measurements of Stunted Rats from Experiments of Osborne and Mendel, 1910-1911.

Control Rats.

	Diet.	Sex.	Age in days.	Weight in grams of—			Hypophysis.	Percentage of water.		Length in mm. of—	
				Body.	Brain.	Cord.		Brain.	Cord.	Body.	Tail.
Rat 96...	Milk	Fem.	178	154.9	1.7346	0.4934	0.0073	78.306	71.139	176	146
Rat 97...	Milk	Fem.	178	164.5	1.6974	0.5007	0.0093	78.473	71.220	183	164
Rat 99...	Mixed	Male	178	175.0	1.8515	0.4810	0.0052	78.623	71.809	181	144
Average..				164.8	1.7612	0.4937	0.0071	78.467	71.389	180	151
Calculated from body-length..........					1.7645	0.5004	......	78.374	71.192	180	.....
Estimated percentage of water from age				......	......	......	78.4	71.2		.....	.....

Body-length to tail-length 1 : 0.83

Stunted Rats.

	Diet.	Sex.	Age in days.	Body.	Brain.	Cord.	Hypophysis.	Brain.	Cord.	Body.	Tail.
Rat 100..	Glutenin	Fem.	178	85.0	1.6323	0.4089	0.0035	78.141	70.775	148	129
Rat 101..	Glutenin	Male	178	71.8	1.5022	0.3781	0.0022	78.272	71.701	139	108
Rat 102..	Glutenin	Male	178	85.7	1.6280	0.3977	0.0033	78.133	71.134	148	125
Average..				80.8	1.5875	0.3929	0.0030	78.182	71.203	145	121
Calculated from body-length..........					1.5896	0.3639	......	......	......	145	.....
Estimated percentage of water from age				......	......	......	78.4	71.2		.....	.....

Body-length to tail-length 1 : 0.83

Formulas.

Brain weight $= 0.569 \log \left(10^{\frac{\text{Body-length}+134}{143}} - 23.7\right) + 0.554$

Spinal cord weight $= 0.585 \log \left(10^{\frac{\text{Body-length}+134}{143}} + 6\right) - 0.795$

Percentage of water (brain) $= 82.62 - 2 \log (\text{Body-weight} - 10)$.
Percentage of water (spinal cord) $= 85.20 - 6.5 \log (\text{Body-weight})$.

Photographs of other rats which have been dwarfed in like ways give evidence of the similarity of the stunts in general appearance with normal animals of the same weight at a much earlier age. Thus, in Plate 1, rat 305, C, weighing 55 grams at the age of 36 days, compares favorably with rat 240, B, dwarfed on a gliadin food mixture, at the age of 140 days, when it weighed 55 grams (cf. Chart CXIII). It is interesting to contrast B with the uppermost photograph A of rat 238, likewise 140 days old and from the same brood but weighing 146 grams, the normal weight for this age. Each was raised under

identical conditions from the age of 38 days, except that rat 238 (see Chart LVI) was fed with a paste containing *casein* and protein-free milk, while in the food of 240 (see Chart CXIII) the casein was replaced by *gliadin*.

Plate 2 shows rat 220, E, fed on gliadin and protein-free milk but weighing only 58 grams, although 148 days old, and, for contrast, rat 168, D, of approximately the size normal for the age of rat 220, is also shown. Figure F shows a normally nourished rat of the same weight as rat 220. This picture is introduced to show that rat 220 has the appearance of a normal rat of corresponding size and weight. All these pictures were taken on exactly the same scale and afford a ready comparison of the relative sizes of the animals.

The interesting photographs of underfed cattle published by Waters, on the contrary, make the change of form in his undernourished animals of stationary weight quite apparent. We are, however, not prepared to assert that careful measurements of our stunted rats will not disclose some trace of similar changes in skeletal form. They must be slight at most; for we have often compared animals long maintained at small stature with properly grown animals which have just reached the same weight, without detecting any deviation from the youthful form in so far as one could judge by mere visual inspection. The photographs speak in the same sense.

The point on which we lay great stress in the foregoing experiments is the fact that the stunting is not attributable primarily to *under-feeding*. Our dwarfed rats have as a rule eaten as adequately as normally nourished animals *of the same size*. The energy factor, as such, thus drops out of the problem. In this respect the experiments are not comparable with those of Waters and of Aron, both of whom accomplished their results by underfeeding with adequate food materials. In our experiments the "energy requirement for maintenance" and the "energy requirement for growth," which together are essential to the developing organism, were both supplied. The rats did not grow primarily at the expense of stored tissue materials: they failed to grow in any sense. *We are obviously dealing with some other feature than insufficient energy supply.* The numerous illustrative experiments which will be cited later are accordingly to be interpreted as instances of *maintenance* without growth. If it is true that growth can only continue when the energy intake exceeds the mere maintenance requirement, it is equally true that an excess of calories does not *per se* insure growth in a suitable animal. Here then is the opportunity to ascertain and differentiate some of the essential qualitative factors: protein, inorganic salts, etc.—their minimum and optimum values.

EFFECT OF STUNTING ON THE GROWTH IMPULSE.

Before proceeding to study the influence of dietary variations on (a) maintenance and (b) growth, respectively, it became necessary to learn whether a more or less temporary inhibition of growth checks or in any degree modifies the capacity to grow (Wachstumstrieb). The literature on this subject by no means reveals a unanimity of opinion, although familiar experience will bring to mind many illustrations of compensated retardation of growth in children.* A few typical experiments may be cited. Rat 36 (male) kept stunted 49 days on a diet of gliadin food† (37 days) followed by casein food mixture† (12 days), showed complete recovery of growth on a mixed diet (see Chart XCVI). The "mixed diet of our animals consists of dog biscuit, sunflower seed, and fresh carrots (with occasional changes and addition of lumps of rock salt). Rat 65 (female) stunted, during 33 days on a diet of casein-zein food,‡ likewise resumed a normal rate of growth as soon as the mixed diet was instituted (see Chart XXXVII).

Special interest is attached to experiments in which after a preliminary stunting period the resumption of growth was accomplished on a diet containing milk as the effective component. Two protocols of the diet during the stunting period are reproduced in Table XXXV, with reference likewise to Charts XXVIII and XXIX.

TABLE XXXV.

Duration of stunting.	Rat 64 (female), 33 days.		Rat 51 (male), 46 days.	
		per cent		per cent
	Casein	12.0	Casein	18.0
	*Zein	6.0	Starch	29.5
	Starch	29.5	Sugar	15.0
Stunting diet..........	Sugar	15.0	Agar	5.0
	Agar	5.0	†Salt mixture I	2.5
	†Salt mixture I	2.5	Lard	30.0
	Lard	30.0		

*The zein was hydrated by the addition of a little water.   †Cf., p. 86.

The curves in these cases are seen to be quite comparable with those of the normally growing rats. Bearing in mind that the animals here studied were continually kept in small cages under actual experimental conditions, the "normal" character of the growth curves makes it evident that the environment is no wise detrimental.

*Cf. Condereau: Recherches chimiques et physiologiques sur l'alimentation des enfants, Paris, 1869; Pagliani: Giornale della reale societa italiana d'igiene, Milano, 1879, I. (Quoted by Hatai: American Journal of Physiology, 1907, XVIII, p. 320.)
†See p. 122.
‡See p. 98. Water was added to this mixture until the zein was well hydrated.

Normal growth, as judged by curve of increase in body-weight, was resumed on a diet consisting of

	per cent.
"Trumilk"	60.0
Starch	16.7
Lard	23.3

Similar experiences are shown after feeding gliadin (Charts XCIX, C) or edestin (Chart LXV).

In the case of rat 37 (Chart XCVII), a stunting period of 49 days on a diet of gliadin food for 37 days, followed by casein food mixture for 12 days, was followed by normal resumption of growth under a dietary régime in which a period of feeding on the above milk-food was alternated with mixed food. Judging by the typical character of the curve of growth in this animal the two types of resuscitation diet, though radically different in origin, are equally efficacious in promoting growth. The growth curve shows little deviation from its usual course incidental to the changes in the dietary.

It may be remarked that the early stunting does not necessarily impair the capacity to breed at a later period when growth is again established. Furthermore, we have found that the milk-fat-starch mixture continued from early life in no wise impairs the potency of rats as breeders. Its nutritive efficiency will be referred to again.

Experiments such as those recorded above give unmistakable evidence of the fact that a considerable period of stunting by no means impairs the "Wachstumstrieb" of these animals. As soon as an appropriate diet is instituted growth begins anew and proceeds with practically the same speed as under normal conditions. By this we mean that a definite increment of gain from some fixed weight requires approximately the same period for its accomplishment as in the case of uninterrupted growth. A rat which will ordinarily grow from 60 grams to 180 grams in body-weight in 60 days will make the same gain even when its growth has been inhibited days or even weeks and its size and form retained at a maintenance level. This will be apparent by comparing, for example, the normal growth curve for both male and female rats with that of the realimented rats, during the same period of time, in Charts CXXII and CXXIII.

It should be emphasized that the situation is here quite different from that developed by Waters and Aron in the experiments on cattle and dogs. With their conditions of underfeeding the animals increase in size (height, etc.) while starving; and during the earlier period of such trials a poorly fed animal may actually gain in height as rapidly as a highly nourished one, fed to the limit of its appetite.*

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*Cf. Waters: The capacity of animals to grow under adverse conditions. Proceedings Society for the Promotion of Agricultural Science, 1908, xxix, p. 15.

The duration of the period of growth of the undernourished animal depends upon the constitutional vigor of the individual and the store of fat which it has accumulated. Quoting Aron: "Dem Einschmelzungsprozess fällt neben dem Fettgewebe in erster Linie die Muskulatur zum Opfer, während die Organe ihm widerstehen, wohl weil sie lebenswichtiger sind."

The results of realimentation in animals which show this "disproportionate" growth, *i. e.*, growth of one part at the expense of another, are not yet satisfactorily ascertained. Waters believes that physiological compensation may result "by an increase in the rate of growth in a period of liberal feeding following a period of low nourishment and low gain. In other words, an animal that is below the normal in size at a given age, through poor nourishment, apparently has the capacity, when liberally fed, to compensate for this loss, in a measure at least, by an increased rate of gain." He also suggests the possibility that growth may be accomplished on a more economical basis—a view which we are not yet ready to accept.

EFFECT OF PARTIAL STARVATION ON BODY-WEIGHT.

Hatai[*] has studied the effect of partial starvation followed by normal diet on the growth of white rats. The "partial starvation" consisted in feeding a diet that is practically devoid of protein, viz, starch and water, during 21 days to animals about 40 days old. The realimentation was continued to the age of maturity, at the end of 200 days. The statistics thus obtained and reproduced in Table XXXVI are presented graphically in Chart XXVI.

TABLE XXXVI.—HATAI'S MEASUREMENTS OF UNDERFED AND REALIMENTED RATS.

	Body-weight.			Total gain.	Ratio between initial and final.
	Initial.	After 21 days.	Final.		
	gm.	*gm.*	*gm.*	*gm.*	
Male, controls............	35.2	63.1	224.4	189.2	1 : 6.37
Male, experimented......	37.6	28.4	242.0	204.4	: 6.43
Female, controls.........	36.3	67.8	†172.6	136.3	: 4.75
Female, experimented....	34.3	27.0	†167.8	133.5	: 4.89

Hatai concluded that, as far as body-weight is concerned, "the experimented rats have completely recovered from the effect of 21 days of partial starvation . . . The recovery in the weight is most astonishing, especially during the first 3 or 4 days, within which time the starved rats regain the weight lost during the 21 days of starvation. Later the increase in weight is very steady, though not as rapid as during the first few days, until the rat has reached the age

*Hatai: American Journal of Physiology, 1907, XVIII, p. 310.
†The body-weight in both control and experimented is small for the age.

of 150 days, and after this age increase in weight is relatively slow. What will happen to such rats during the later portions of the span of life has yet to be determined in order to answer the question whether this partial starvation in early life has any influence either on longevity or the onset of old age." (p. 314–315.)

EFFECT OF PARTIAL STARVATION ON NERVOUS SYSTEM.

Though the period of retarded growth was eventually completely compensated in Hatai's animals, in so far as the weight of the body and central nervous system are concerned, the chemical composition of the brain and spinal cord was not entirely free from the effect. As the result of an extended investigation of the effects of underfeeding on the nervous system, Donaldson*has arrived at the conclusion that one of the characteristics of growth, the change in the water content of the brain, has not been arrested like the increase of the animal in size and body-weight, but apparently accelerated. He states:

The underfed group are in this character similar to somewhat older animals. Evidence further points to the continued formation of the medullary sheaths with advancing age even in rats which are underfed, i. e., underfeeding does not arrest medullation. Underfeeding which stops growth of the body and retards that of the nervous system does not modify the percentage of water in the spinal cord, while it does reduce it in the brain—the amount of this reduction being less in the cases where the underfeeding is less severe.†

With respect to the possible psychological effects of such underfeeding and return to normal diet Donaldson says:

So far as our tests show, such an experience does not modify the rat's ability to learn, for, by a series of experiments, it has been possible to determine that such a rat can learn to get its food under complicated conditions just as well and as rapidly as a normal animal (Hayes).‡

The preceding facts as to resuscitated rats are recorded here— despite the fact that this temporary stunting was produced by underfeeding (rather than unsuitable feeding as in our experiments)— because they suggest that the real story of the condition of the animals may perhaps not be revealed by the external evidences of growth. It is not at all impossible that the rats which we have dwarfed for months may have experienced some continued subtle changes in the make-up of the nervous system despite the appearance of unchanged youth which they manifest. Measurements of size and weight alone may not suffice to disclose the real physiological status of the animal, especially in respect to the development of the nervous functions and structures, which are singularly pro-

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*Donaldson: Journal of Comparative Neurology, 1911, XXI, p. 139.
†Donaldson: ibid., p. 169.
‡Donaldson: Journal of Nervous and Mental Disease, 1911, XXXVIII, p. 262.

tected even during starvation. This is seen to be true in the series of stunted animals fed on the glutenin mixture in our experiments (p. 72). There is a large field of investigation still open here with important bearings on the problems of retarded growth in man. According to Donaldson* "the progressive diminution of the percentage of water in the central nervous system with advancing age is to be regarded as an index of fundamental chemical processes, which take place in the more stable constituents of the nerve cells. These processes are but little modified by changes in the environment and taken all together constitute a series of reactions which express not only the intensity of the growth process in the nervous system, but also the span of life characteristic for any given species." Possibly, then, the further study of the nervous system in connection with our experiments may throw light on the phenomena of malnutrition (which our stunting experiments primarily represent) as well as those of undernutrition or starvation.

It may be well here to note that the experience of Donaldson† indicates the main features of human growth to be well represented in the albino rat. So good is the essential correspondence that there is every reason to continue the work on this form. The striking difference is that the rat grows some thirty times as rapidly as man.

COMPARISON OF MILK AND MIXED DIET.

The failure either to induce substantial growth in young rats or to satisfy completely the maintenance requirement of older animals during very long protracted periods on the mixtures of isolated foodstuffs thus far reported raises the question as to what constitutes an ideal nutriment for a rat. The suitability of mixed diet is beyond question. The favorable experiences with dried milk powder (some of which have been recorded on pages 75 and 76) early directed our attention to this product. Rats were not only resuscitated after nutritive decline and suitably maintained, but also grown from early age on pastes in which the milk powder (with lard and starch) constituted the mixture. The commercial brand "Trumilk"‡ employed by us has been analyzed at the Connecticut Agricultural Experiment Station with the following results:

	Per cent.
Water	3.8
Total solids	96.2
Protein ($N \times 6.38$)	25.6
Fat	27.4
Lactose	37.2
Ash	6.0

*Donaldson: Journal of Comparative Neurology, 1910, XX, p. 143.
†Cf. Donaldson: Journal of Nervous and Mental Disease, 1911, XXXVII, p. 258.
‡This product was kindly furnished to us in powder form by the Merrell-Soule Co., Syracuse, N. Y.

The preparation apparently contains a small excess of iron over that found in cow's milk—probably as a contamination from the desiccating process used. It is obtainable in easily manipulated form and with the addition of a small amount of nitrogen-free lard and starch forms a food paste readily consumed by rats. These pastes have been used, either with or without our earlier standard salt mixture (I),* as follows:

	Per cent.	Per cent.
"Trumilk"	60.0	60.0
Starch	16.7	15.7
Lard	23.3	23.3
Salt mixture I	0.0	1.0
	100.0	100.0
Nitrogen content	2.5	2.5

We have carried rats through the period of growth as well as pregnancy on this diet alone, from the time that they were removed from the mother (cf. Charts XXXI, XXXII, and XXXIII).

As a further illustration of the excellent nutritive properties and physiologically appropriate "combination" of food ingredients in the milk food-mixture, illustrative charts are appended to show the recovery of rats moribund after prolonged periods of malnutrition, with lack of inorganic salts in the dietary (Charts XXXIV and XXXV). Many similar illustrations might be reproduced, giving evidence of the perfect realimentation of rats by the use of the milk food (cf. Charts XXVIII, LXV, XCIX, and C).

Remembering that our earlier trials with casein, the chief protein ingredient of the milk powder, and with combinations of casein and other proteins were at best successful only in maintaining nutritive equilibrium—and that not indefinitely—and were never adequate for the manifestation of real growth, we directed our attention to the non-protein constituents of milk. After numerous failures to modify the inorganic and non-protein ingredients of our dietaries by altering the relation of proportions of the various ions as well as the character of the carbohydrates and fats, it occurred to us that the protein-free portion of the milk might give the clue to the successful feeding of proteins which did not appear to be the inefficient factors in our cases of malnutrition. Accordingly a product was prepared as follows:

Perfectly fresh centrifugated milk, nearly free from fat, was precipitated in lots of about 36 liters by diluting with 7 liters of distilled

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*This mixture, prepared in imitation of Röhmann's successful product and empirically found by use to be the most satisfactory of the different combinations tried, has the following composition:

	Grams.		Grams.
Ca$_3$(PO$_4$)$_2$	10.0	Mg citrate	8.0
K$_2$HPO$_4$	37.0	Ca lactate	8.0
NaCl	20.0	Fe citrate	2.0
Na citrate	15.0		100.0

(Cf. our previous report, Feeding experiments with isolated food-substances, Publication No. 156, Carnegie Institution of Washington, p. 32.)

water which contained 1.64 c.c. of concentrated hydrochloric acid. The flocculent precipitate of casein was strained out on cheesecloth and the very nearly clear solution was filtered through a pulp filter. The filtrate, which at the most was very slightly turbid from suspended fat, was tested carefully by the alternate addition of dilute alkali and acid to determine whether any more casein could be separated from it. The addition of alkali caused a slight precipitate which did not increase on adding more alkali or dissolve on the addition of even relatively large amounts of alkali. This was presumably chiefly calcium phosphate. The addition of acid in no case caused any further precipitation. The filtered milk serum was then heated to boiling for a few minutes and filtered. The filtrate, which was in all cases water clear, was then neutralized to litmus with a dilute solution of sodium hydroxide and evaporated to dryness on a steam bath at a temperature of about 70°. The product thus obtained formed a friable, pale yellow mass which was easily reduced to a fine powder by grinding in a mill. Several grams of this powder were tested for protein by dissolving in about 30 c.c. of water containing a little hydrochloric acid and warming gently. The solution was then saturated with ammonium sulphate. The precipitate, which appeared to consist chiefly of calcium sulphate, was separated by centrifugation, dissolved in a little water, and potassium hydrate solution and copper sulphate added. The solution showed no evidence of the biuret reaction until it was saturated with potassium hydroxide and shaken with alcohol. It then separated into two layers, the upper alcoholic layer showing a slight but positive biuret reaction. Millon's reaction tried on portions of 2 or 3 grams of the substance did not give a positive reaction. Nitrogen determinations in several lots of the protein-free milk powder thus made showed them to contain 0.66, 0.59, 0.60, 0.72, 0.71, 0.67, 0.75 per cent of nitrogen. Munk* states that if the proteins of milk are precipitated by alcohol, or separated according to Hoppe-Seyler, from one-thirtieth to one-fifteenth of the protein remains dissolved. All the proteins can be precipitated only by tannin in the cold or by copper hydroxide on heating. He further states that cow's milk contains about one-sixteenth of its nitrogen in non-protein form. Since our protein-free milk powder was equal to 50 per cent of the total solids of the milk, it should, if Munk's statements are correct, contain 0.48 per cent of non-protein nitrogen, thus leaving at the most only 0.28 per cent of protein nitrogen, equal to 1.69 per cent of protein. Since 100 grams of the food mixture employed in our experiments contained 28.2 grams of protein-free milk powder, we can assume that at the most the food pastes thus made contained only 0.48 per cent of milk protein. The protein-free

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*Munk: Virchow's Archiv für pathologische Anatomie, 1893, 134, p. 501.

milk powder thus produced as above described left about 14.5 per cent of inorganic matter on ignition. This includes not only the inorganic constituents of the milk, although by no means in the combination in which they occur in the mammary secretion, but also the inorganic salts which were formed by the addition of the hydrochloric acid used to precipitate the casein and also the sodium salts which resulted from neutralizing the milk serum with sodium hydroxide solution.

EXPERIMENTS WITH ISOLATED PROTEINS AND "PROTEIN-FREE" MILK.

The use of this product (which we shall designate as protein-free milk) as an adjuvant to isolated proteins to furnish the inorganic elements of the diet has succeeded beyond our expectation. When employed, for example, in combination with various proteins, in the proportion in which its ingredients occur in the complete milk food already used (see page 76), it induces normal growth. Added during the periods of nutritive decline to food mixtures which no longer suffice to maintain rats, recovery has manifested itself in practically every case. Where, as in the case of zein, gliadin, or hordein feeding, no advantage has been obtained by the use of the protein-free milk, it has become obvious that the protein *per se* is the defective food constituent. Thus at length we have found a method of controlling or furnishing some of the most essential non-protein factors in the diet, so that the value of the individual proteins can be investigated under much more favorable conditions than formerly.

Numerous charts (see p. 103 fig.) present the graphic records of feeding experiments with casein, edestin,* glutenin,* glycinin,* gliadin,* hordein,* ovalbumin,† and lactalbumin,‡ showing appropriate growth, or maintenance, according to the age at which the animals were started on the use of the protein-free milk as the non-protein component in place of the earlier inorganic salt mixture.

It might be objected, after superficial consideration of these results, that the favorable outcome (especially for growth) is due to milk protein contaminating the "protein-free milk" component of the diet. Aside from the fact that the amount of possible contamination is at most small, evidence of the untenability of such a theory is available from several sources. In the first place, growth has not followed the use of *all* proteins when the protein-free milk was added to them.

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*For the preparation of these vegetable proteins see T. B. Osborne: Darstellung der Proteine der Pflanzenwelt, Abderhalden's Handbuch der biochemischen Arbeitsmethoden, 1909, II, p. 270.

†This was prepared by Hopkins's method and was free from conalbumin. Cf. Osborne, Jones, and Leavenworth: American Journal of Physiology, 1909, XXIV, p. 252.

‡The preparation of this is described on p. 81.

The results can be grouped in two series, viz:

Diet = Isolated protein, protein-free milk, starch, agar, fat.

Group I.—Young rats.	Group II.—Young rats.

Active growth with—
  Casein (Charts XLVI, XLVII, LII, LIII,
    LIV, LV, LVI, LVII, LVIII, LIX, and LX.
  Ovalbumin (Charts XC and XCI).
  Lactalbumin (Charts XCII and XCIII).
  Edestin (Charts LXXI, LXXII, LXXIII,
    LXXIV, LXXV, and LXXVI).
  Glutenin (Charts LXXXVII, LXXXVIII,
    and LXXXIX).
  Glycinin (Charts XCIV and XCV).
	Little or no growth with—
	  Gliadin (Charts CVIII, CIX, CX, CXI,
	    CXII, CXIII and CXIV).
	  Hordein (Charts CXXIV and CXXV).

The failures in group II lead to the conclusion that the proteins, gliadin and hordein, are inadequate for the functions of growth. We are presumably dealing with a chemical inadequacy rather than any toxicity and consequent lack of growth, judging by the fact that the gliadin and hordein rats are maintained in good, nutritive condition even in the absence of growth. Their body-weight is scarcely changed at all. Without the use of the protein-free milk or fæces-feeding gliadin rats have usually declined (Charts XCVIII, XCIX, and C).

A second reason why the success of these trials is not due to the presence of possible minute contaminations with milk protein is discoverable in Charts XLIII, XLIV, XLV, XLVIII, XLIX, L, LI, CVIII, CIX, CX, and CXI. Here the addition of not inconsiderable portions (5 to 30 per cent) of the actual milk food to the earlier inefficient protein mixtures is incapable of bringing about growth in any degree equal to that at once initiated when the protein-free milk is added in relative abundance.

Further evidence that a trace of milk proteins is not responsible for the growth of the rats fed with mixtures containing our protein-free milk powder is furnished by experiments in which successively larger quantities of the milk food are added to the gliadin food. Here we see that growth gradually increases with the larger additions of the milk food, although with even as much as 30 per cent in the food the rate of growth is much below normal. With additions of 5 or even 20 per cent of the milk food, the rate of growth is very slow, as shown by Charts CIV, CV, CVI, and CVII. That this result is to be attributed to the proteins introduced in the milk food and not to a combination of a small quantity of milk proteins together with a sufficient quantity of the inorganic or other constituents of the milk is shown by experiments now in progress in which the addition of the milk food to the gliadin and protein-free milk food is producing normal growth. In this mixture we have all of the constituents of

the protein-free milk present in the same proportions as in our milk food, but less than one-third of the protein constituents of the milk. It is therefore evident that only a small proportion of the protein constituents of the milk are required to produce normal growth, and it may be assumed that the presence of a small quantity of milk proteins in our protein-free milk powder would manifest itself by at· least some slight growth.

DISCUSSION OF THE RESULTS AND THEIR BEARINGS.

We have stated that by our plan a biological comparison of different proteins in respect to their rôle in growth can at length be made.   Our work in this direction must be regarded as barely begun. Nevertheless it is of interest to speculate as to the indications already gained and the outlook for future work.   A comparison of the two groups of proteins—those adequate and those inadequate for growth purposes—at once reveals the fact that the latter category comprises proteins (gliadin, hordein, zein) commonly spoken of as chemically "incomplete."   They lack one or more of the amino-acid complexes which are obtainable from the so-called "complete" proteins.   None of them furnish glycocoll or lysine, and zein in addition is devoid of tryptophane.   By feeding relatively small quantities of proteins like casein with gliadin growth begins at once.   Here we can determine the minimum of suitable protein to satisfy this growth requirement— a study already begun (cf. Charts CXX, CXXI, CXXII, and CXXIII).   The addition of amino-acids to "complete," as it were, the inadequate proteins can now be studied amid controllable factors; the biological rôle of hydrolyzed proteins and the significance of complete hydrolysis or digestion in nutrition can be examined anew.

The experiences which have demonstrated the striking differences in value of the individual proteins and the small proportion of casein which suffices to induce growth instead of standstill (cf. Charts CXX, CXI, CXXII, and CXXIII, for example) emphasize the importance of the *purity* of the protein fed.   We have devoted much labor and incurred a very considerable expense to obtain proteins in a form as uncontaminated as present methods will permit.   The products used were as pure as one would expect them to be if employed for purposes of refined protein analysis.   Had less perfect products been employed it is quite conceivable and indeed likely that the admixtures would have sufficed to alter completely the outcome of many experiments.   For example, gliadin is prepared free from glutenin only be very careful purification methods; and although the nutritive properties of these two companion proteins are extremely unlike, as clearly indicated by our trials, a failure to effect a complete separation of a little glutenin from gliadin would have been sufficient to prevent the deficiencies of the latter from exhibiting themselves.   Or

again, failure to purify carefully a protein like casein will vitiate the study of a problem like the synthesis of amino-acids. Pure casein is glycocoll-free; and the continued feeding of such a product as the sole protein of the dietary enables one to make deductions respecting the synthesis of glycocoll. The use of crude commercial protein preparations can never satisfy the requirements of refined study in this domain, where small effects continued over long periods are of great importance. We believe, therefore, that such considerations justify the energy and expense which have been put into the work.

In relation to the much-discussed problem of the relative value of organic *vs.* inorganic phosphorus in nutrition, our data after feeding phosphorus-free edestin to growing rats (cf. Charts LXXV and LXXVI) show a success quite as great as that with phosphorus-containing casein (cf. Charts LVI, LVII, LVIII, LIX, and LX). The animals must here have synthesized their phosphorus compounds from inorganic phosphorus. Whether milk production and other functions calling for such synthetic reactions will continue adequately is open to investigation. It is also noteworthy that all of our animals grow on a dietary that is purine-free, or essentially so. Here the question of purine synthesis suggests itself. It is apparent, *e. g.*, in the case of gliadin, that the grown as well as ungrown rats may be *maintained* for long periods on single proteins.

With such an ideal non-protein dietary component at hand amino-acid substitutions can be attempted in the adult as well as in the growing animal. The protein minimum (or minima) is also open to accurate investigation. With a method of feeding devised which will permit a differentiation between growth and maintenance, which furnishes an energy-yielding protein-free component that is appropriate, and leaves the protein as the sole variable in the dietary, we believe that further contributions can be made to the problems of nutrition.

In the preparation of the large quantities of carefully purified proteins required for these experiments, we have been assisted by Mr. Charles S. Leavenworth, Mr. Owen Nolan, Mr. Leigh I. Holdredge, and Mr. Lawrence Nolan, whose valuable cooperation we are glad to acknowledge here.

THE CHARTS AND THEIR EXPLANATIONS.

In the following charts, to which reference is made in various places in the text, the abscissæ of the curves represent days and the ordinates actual body-weight (solid line) or food-intake (dotted line) in grams. In some of the charts the average (normal) curve of growth, plotted from body-weight data available for normally growing animals of the same sex, is represented by a broken line for comparison. The food-intake curve is plotted from the quantities of food eaten per week. The numbers on the body-weight curves indicate the time at which changes in the character of the feeding were instituted. All curves in this paper are plotted on the same scale, so that they are directly comparable.

Salt mixture I, to which reference is frequently made, was composed of—

		Grams.
$Ca_3 (PO_4)_2$		10.0
K_2HPO_4		37.0
NaCl		20.0
Na citrate		15.0
Mg citrate		8.0
Ca lactate		8.0
Fe citrate		2.0
		100.0

INDEX OF CHARTS WITH REFERENCE TO FOOD-MIXTURES AND PROTEINS FED.

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Chart XXII.

Chart XXII shows average normal rates of growth of male and female white rats according to Donaldson and to Osborne and Mendel. In our experience the female rat does not attain as large a size as in Donaldson's experiments. The growth curves coincide until the animals reach an age of about 70 days.

CHART XXIII.

Body weight

Mixed food

Normal rate of growth-rate (Donaldson)

Days

Grams
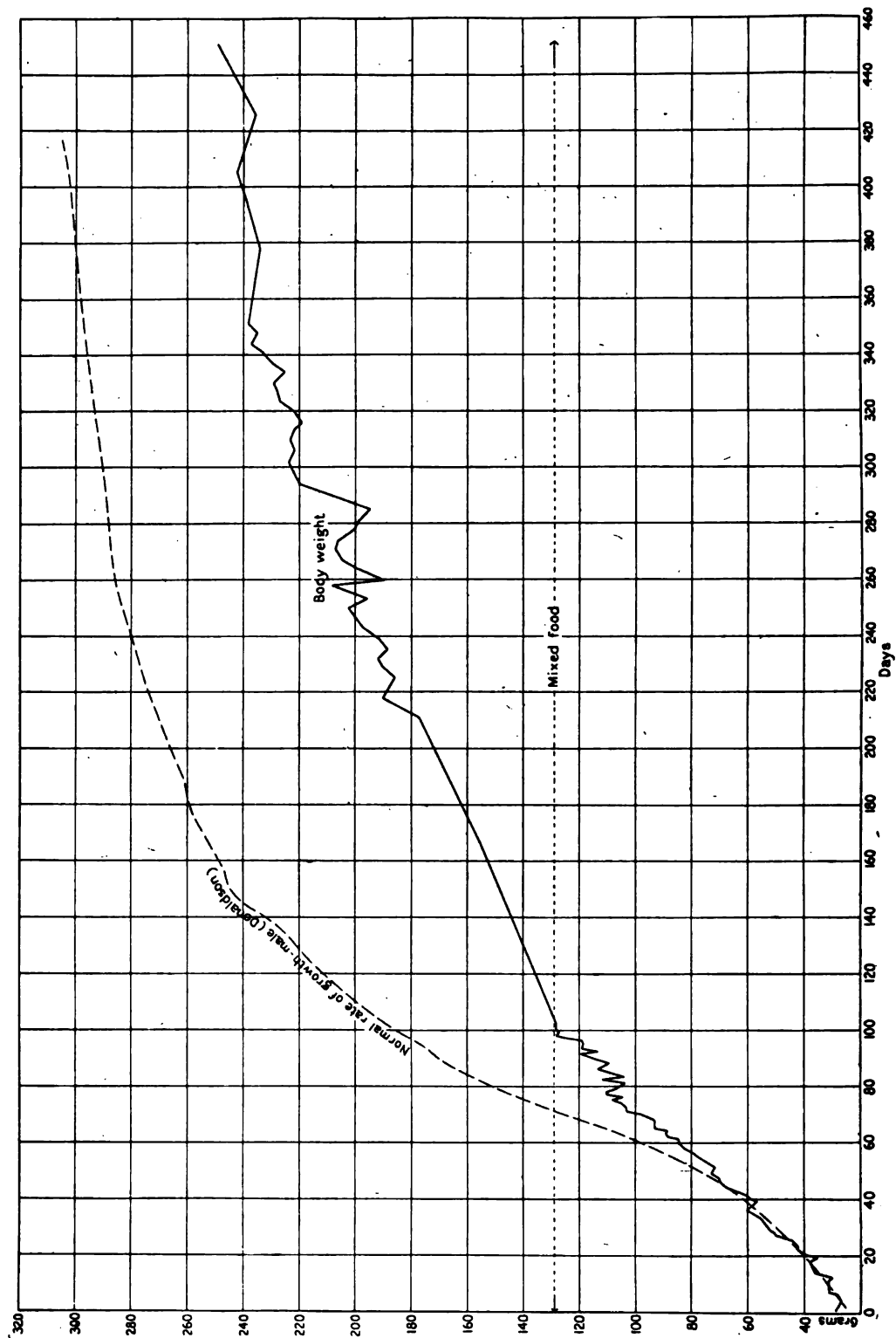
Chart XXIII (rat 48, male) shows the growth of the male rat from early life, under cage conditions adopted for experimental feeding. The animal was fed 452 days on mixed food, consisting of dog-biscuit, sunflower and other seeds, fresh vegetables, and salt.
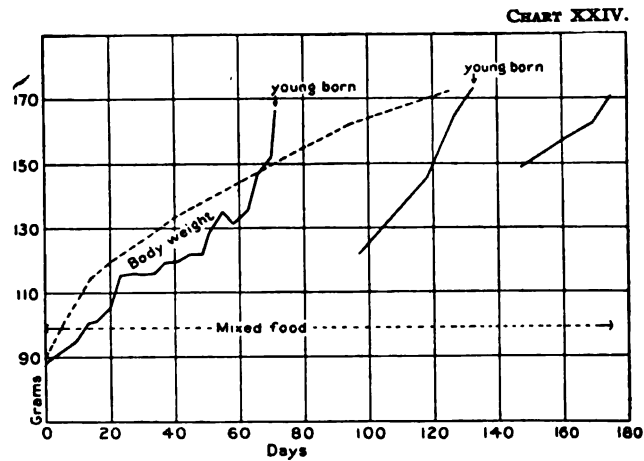
CHART XXIV.

Charts XXIV (rat 166, female) and XXV (rat 156, female) show the typical growth of female rats, including pregnancy, under cage conditions. The animals were fed on mixed food.
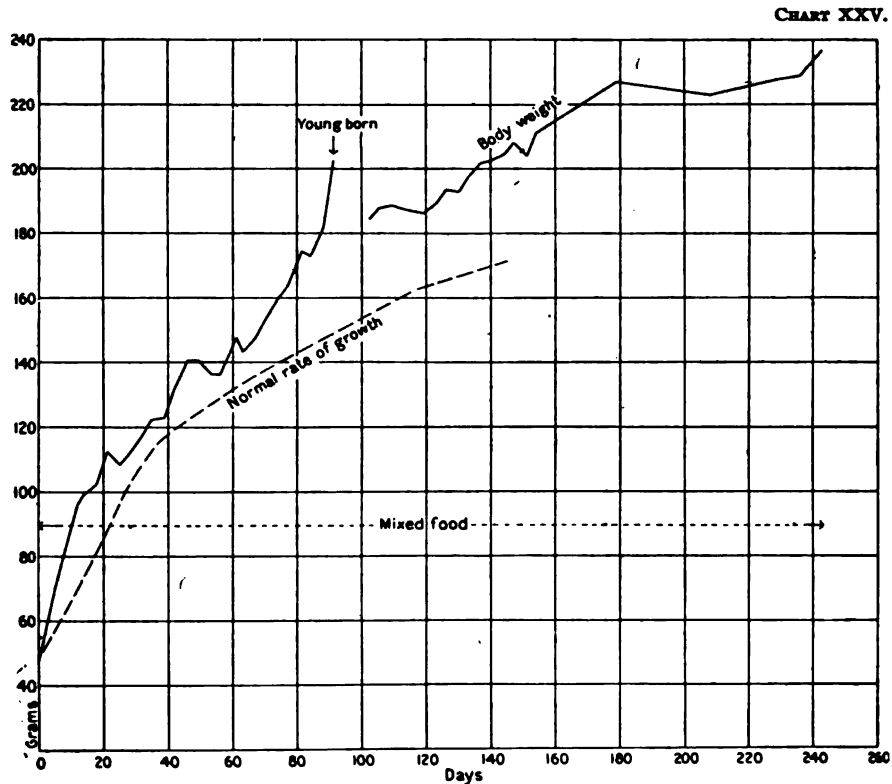
CHART XXV.
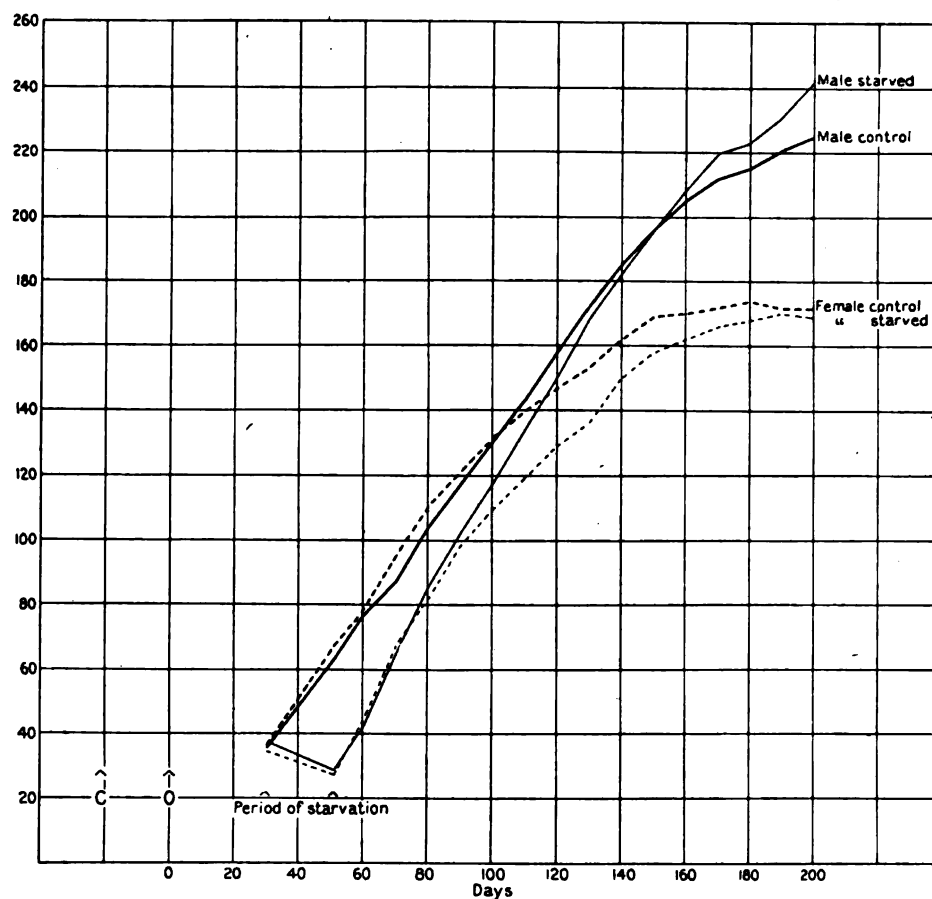
CHART XXVI.

Chart XXVI (curves, from Hatai, American Journal of Physiology, 1907, XVIII, p. 311) shows the body-weights of albino rats at different ages. C, conception, and O, the date of birth 21 days after conception. An illustration is given of the influence on growth of a period of 21 days of starvation during early life.

Chart XXVII.

Constituents.	Per. 1.	Per. 2.	Per. 3.	Per. 4.	Per. 5.
	p. d.	p. d.	p. d.	p. d.	p. d.
Dog biscuit	58.4	70.0	0.0	0.0	0.0
Lard	41.6	30.0	10.0	10.0	10.0
Hempseed	0.0	0.0	46.0	46.0	50.0
Starch	0.0	0.0	42.0	42.0	38.0
NaCl	0.0	0.0	2.0	0.0	0.0
Salt mixture I	0.0	0.0	0.0	2.0	2.0
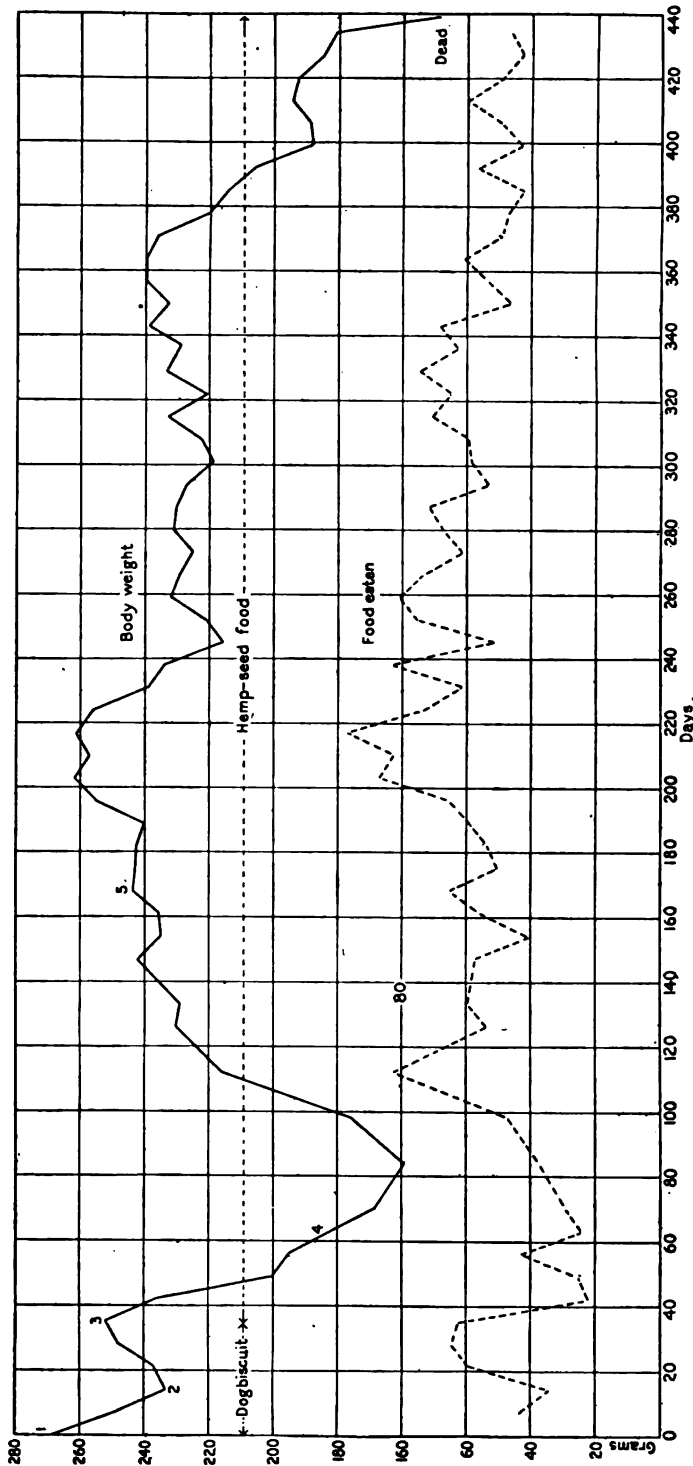
Chart XXVII (rat 18, male) shows the possibility of feeding the same food-mixture (hempseed paste) for a very long period. The diets of this animal for 5 periods were as shown in the table. The hempseed paste was fed for 404 days. Other data will be found on pp. 21–23 in Publication 156, Part I, of the Carnegie Institution of Washington. The food intake was nearly uniform and adequate until near the end of the animal's life. Death was caused by pulmonary disease.

CHART XXVIII.

Constituents.	Per. 1.	Constituents.	Periods 2 and 4.	Per. 3.
	p.c.		p.c.	p.c.
Casein	12.0	Truemilk	60.0	60.0
Zein	6.0	Starch	16.7	15.7
Starch	20.5	Salt mixture I	0.0	1.0
Sugar	15.0	Lard	23.3	23.3
Agar	5.0			
Salt mixture I	2.5			
Lard	30.0			

Chart XXVIII (rat 64, female) shows a period of stunting during 33 days in early life, followed by resumption of growth and maintenance on a milk diet for more than 300 days. The animal died of an intercurrent disease. The diets during the several periods were as shown in the table. Observe that the essential change during the long period of milk-paste feeding consisted in modifying the inorganic constituents of the food; also note the entire absence of roughage or agar in the diet after period 1.

Chart XXIX.

Constituents.	Per. 1.		Constituents.	Periods 2 and 4.	Periods 3 and 5.
	g. d.			g. d.	g. d.
Casein........	18.0		Truemilk.......	60.0	60.0
Starch........	29.5		Starch.......	16.7	15.7
Sugar........	15.0		Salt mixture I.	0.0	1.0
Agar........	5.0		Lard.........	23.3	23.3
Salt mixture I.	2.5				
Lard........	30.0				
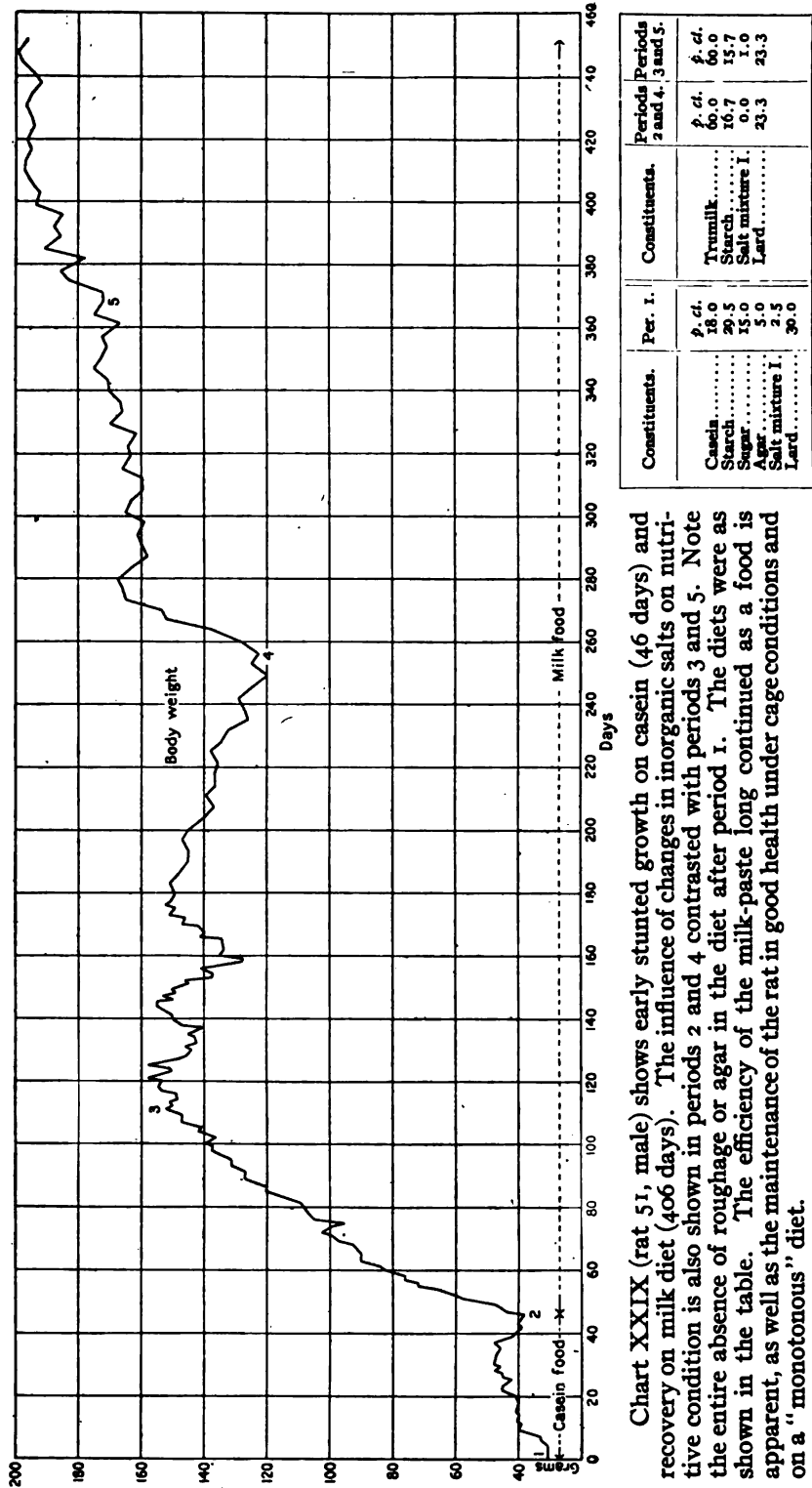
Chart XXIX (rat 51, male) shows early stunted growth on casein (46 days) and recovery on milk diet (406 days). The influence of changes in inorganic salts on nutritive condition is also shown in periods 2 and 4 contrasted with periods 3 and 5. Note the entire absence of roughage or agar in the diet after period 1. The diets were as shown in the table. The efficiency of the milk-paste long continued as a food is apparent, as well as the maintenance of the rat in good health under cage conditions and on a "monotonous" diet.

CHART XXX.
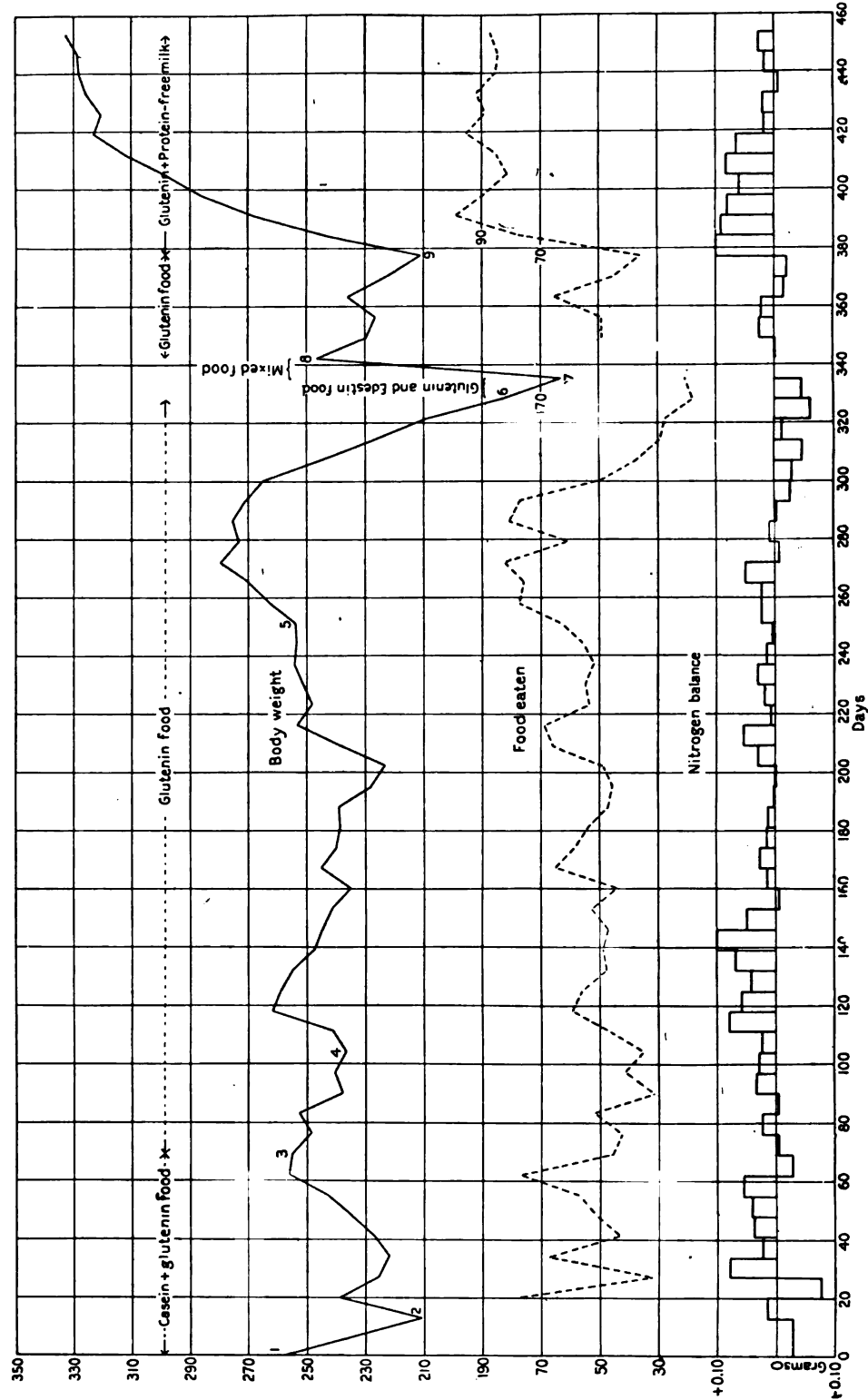
Chart XXX (rat 71, male) shows long-continued feeding of isolated foodstuffs and also long-continued maintenance on glutenin from wheat as the only protein. The history of the animal is on p. 59. The diets were as follows:

Constituents.	Per. 1.	Per. 2.	Per. 3.	Per. 4.	Periods 5 and 8.
	p. ct.	p. ct.	p. ct.	p. ct.	p. ct.
Glutenin	6.0	6.0	16.36	18.0	18.0
Casein	12.0	12.0	0.0	0.0	0.0
Starch	29.5	24.5	22.27	14.5	34.5
Sugar	15.0	15.0	13.63	15.0	20.0
Agar	5.0	5.0	4.54	5.0	5.0
Salt mixture I	2.5	2.5	2.27	2.5	2.5
Lard	30.0	35.0	40.93	45.0	20.0

Constituents.	Per. 6.	Per. 7.	Constituents.	Per. 9.
	p. ct.			p. ct.
Glutenin	9.0	Mixed	Glutenin	18.0
Edestin	9.0	food.	Protein-free milk	28.2
Starch	33.5		Starch	23.8
Sugar	18.5		Agar	5.0
Agar	5.0		Lard	25.0
Salt mixture I	2.5			
Lard	23.5			

Chart XXX further shows the possibility of maintaining an animal satisfactorily under our cage conditions for 458 days. Attention is particularly directed to period 9, during which the only change in the diet consisted in substituting protein-free milk for some of the non-protein components of the dietary. The lowest line represents the nitrogen balance of the rat.
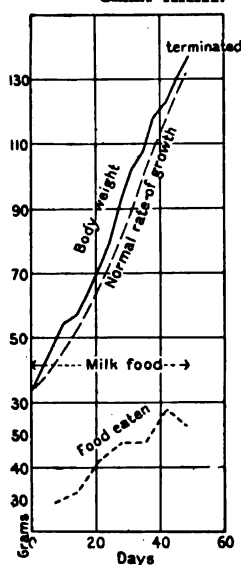
CHART XXXI. **CHART XXXII.**
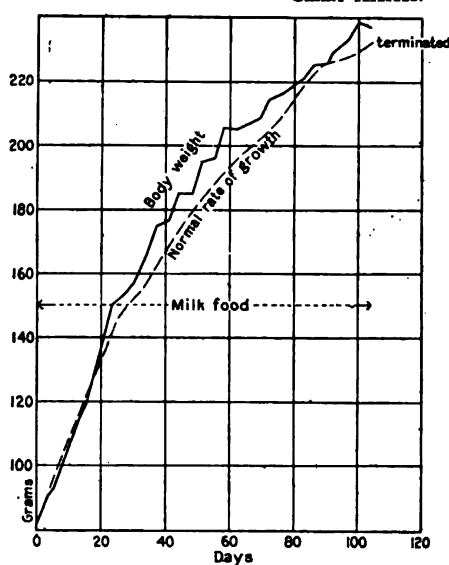
Chart XXXI (rat 222, male) shows early growth curve of male on milk diet, having the following composition: Trumilk, 60.0 p. ct.; starch, 15.7 p. ct.; salt mixture I, 1.0 p. ct.; lard, 23.3 p. ct.

Chart XXXII (rat 195, male) shows normal growth curve of male on milk diet, having the following composition: Trumilk, 60 p. ct.; starch, 16.7 p. ct.; lard, 23.3 p. ct.
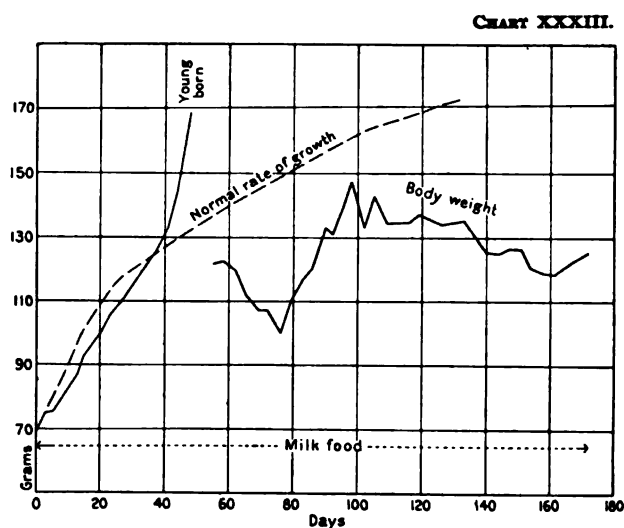
CHART XXXIII.

Chart XXXIII (rat 181, female) shows growth and normal pregnancy of female on milk food, consisting of Trumilk, 60 p. ct.; starch, 15.7 p. ct.; salt mixture I, 1.0 p. ct.; lard, 23.3 p. ct.
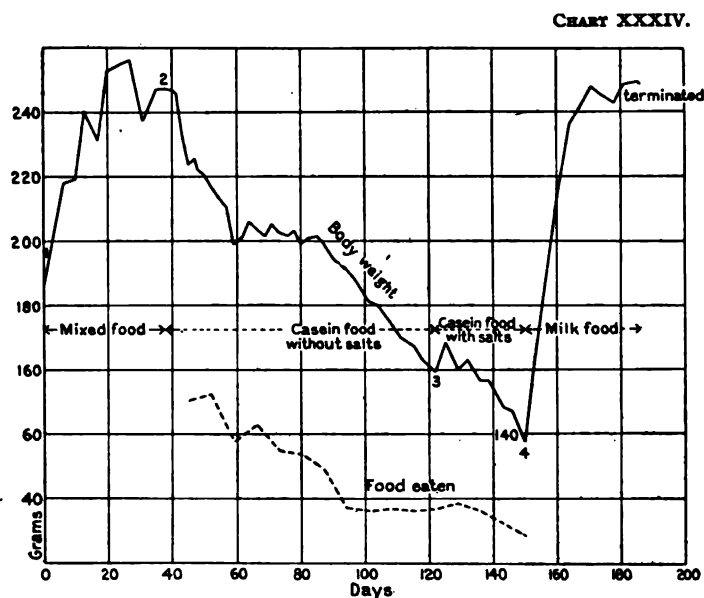
CHART XXXIV.

Chart XXXIV (rat 106, male) shows malnutrition induced by lack of inorganic salts in the dietary and subsequent perfect recovery on milk-paste. The diet was mixed food for period 1; for the remaining periods as follows:

Constituents.	Per. 2.	Per. 3.	Constituents.	Per. 4.
	p. ct.	*p. ct.*		*p. ct.*
Casein	18	18.0	Trumilk	60.0
Starch	25 to 32.5	32.5	Starch	15.7
Sugar	17 29.5	21.9	Salt mixture I	1.0
Agar	0 5.0	0.0	Lard	23.3
Salt mixture I	0 0.0	2.6		
Lard	20 35.0	25.0		
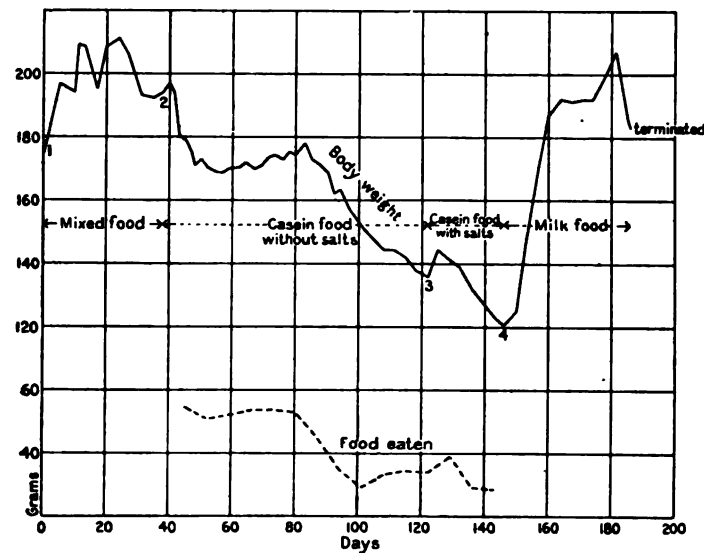
CHART XXXV.

Chart XXXV (rat 110, female) shows malnutrition induced by lack of inorganic salts in the dietary and subsequent perfect recovery on milk-paste. The diet consisted of mixed food for period 1, and as follows for the remaining periods:

Constituents.	Per. 2.	Per. 3.	Constituents.	Per. 4.
	p. ct.	p. ct.		p. ct.
Casein.............	18	18.0	Trumilk..........	60.0
Starch............	25 to 32.5	32.5	Starch...........	15.7
Sugar.............	17 29.5	21.9	Salt mixture I....	1.0
Agar..............	0 5.0	0.0	Lard.............	23.3
Salt mixture I.....	0	2.6		
Lard..............	20 35.0	25.0		

CHART XXXVI.
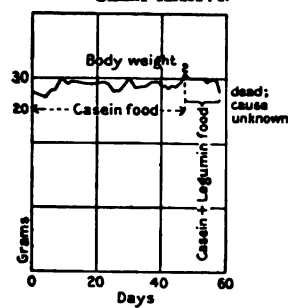
Chart XXXVI (rat 54, male) shows the maintenance for 46 days of a very small rat, without growth, on a diet in which casein formed the sole protein. The composition of the food was as shown herewith:

Constituents.	Per. 1.	Per. 2.
	p. ct.	p. ct.
Casein.............	18.0	9.0
Pea legumin.....	0.0	9.0
Starch...........	29.5	29.5
Sugar............	15.0	15.0
Agar.............	5.0	5.0
Salt mixture I...	2.5	2.5
Lard.............	30.0	30.0

CHART XXXVII.
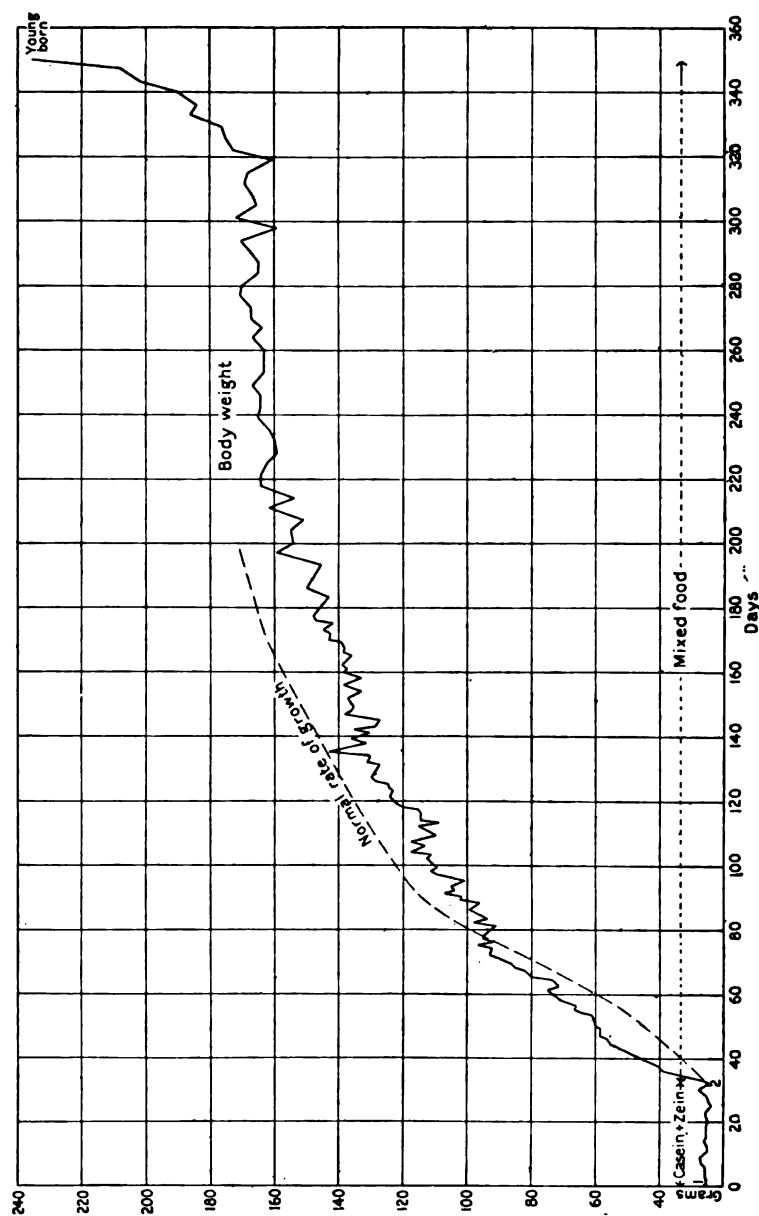
Chart XXXVII (rat 65, female) shows stunting for 33 days during early life, followed by normal growth and pregnancy on mixed food. In addition to the typical growth during 317 days, the curve emphasizes the unaltered "capacity to grow" after stunting by improper diet. The diet during period 1 was as shown herewith.

	p. ct.
Casein	12.0
Zein	6.0
Starch	29.5
Sugar	15.0
Agar	5.0
Salt mixture I.	2.5
Lard	30.0

CHART XXXVIII.
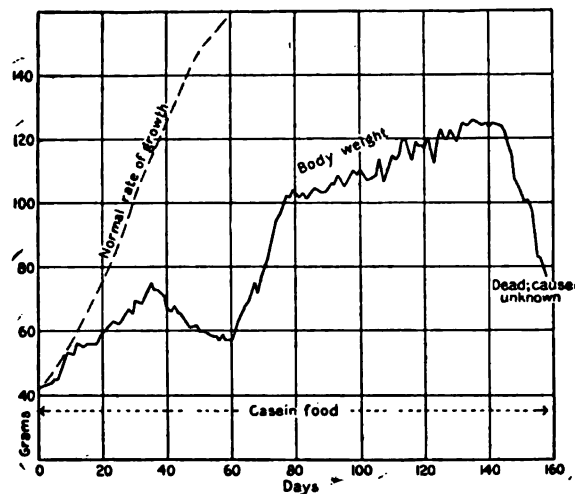
Chart XXXVIII (rat 50) shows maintenance for 158 days on a diet in which casein formed the sole protein. The composition of the food was as shown herewith:

	p. ct.
Casein	18.0
Starch	29.5
Sugar	15.0
Agar	5.0
Salt mixture I.	2.5
Lard	30.0

CHART XXXIX.
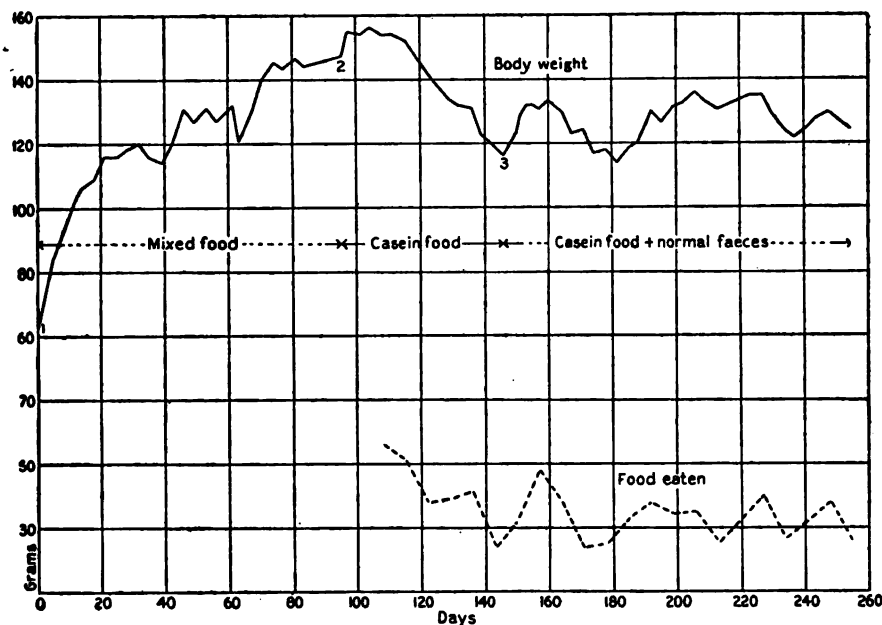
Chart XXXIX (rat 145, female) shows the effect of feeding a diet of isolated food substances in which casein formed the sole protein. Period 1 represents the normal growth of the animal on a mixed food. The casein feeding began with period 2. The influence of fæces of normally fed animals in preventing decline in body-weight is shown during period 3. As shown by the food intake, the favorable effect is not due to an increased consumption of food. The diet during period 1 consisted of mixed food; during periods 2 and 3 as shown in table.

Periods 2 and 3.

	p. ct.	
Casein	18.0	....
Starch	32.5	....
Sugar	21.9 to 26.9	
Agar	10.0	5.0
Salt mixture I.	2.5	2.6
Lard	20.0	25.0
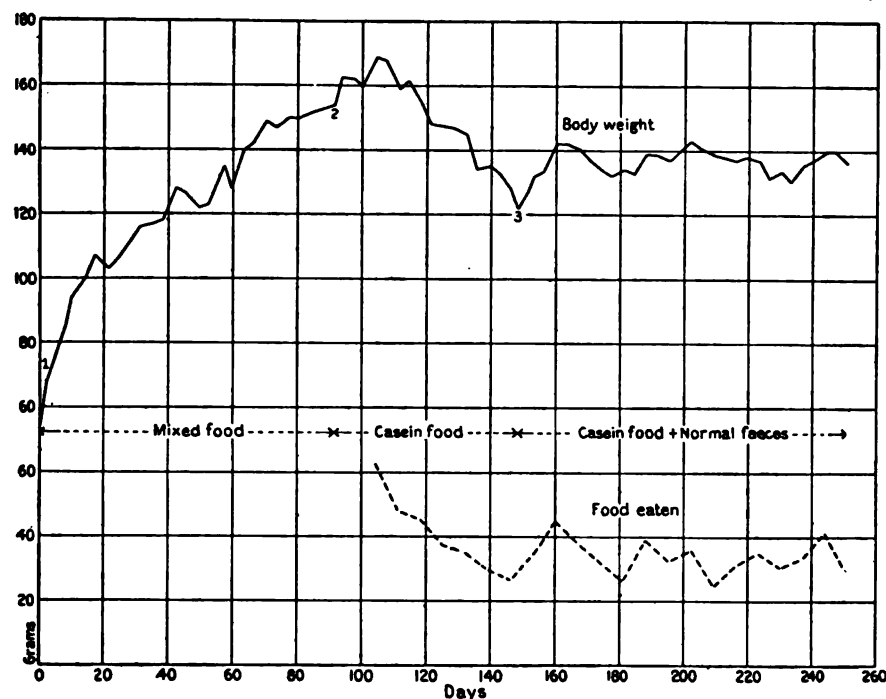
CHART XL.

Chart XL (rat 150, female) shows the influence of a diet containing a mixture of isolated foodstuffs in which casein was the sole protein. Period 1 represents the normal growth of the animal on a mixed food. The casein feeding began with period 2. The influence of faeces of normally fed animals in preventing decline in body-weight is shown during period 3. As shown by the food intake the favorable effect is not due to an increased consumption of food. The diet during period 1 consisted of mixed food; during periods 2 and 3 as shown herewith.

Periods 2 and 3.

	p. ct.	
Casein	18.0	....
Starch	32.5	....
Sugar	21.9 to 26.9	
Agar	0.0	5.0
Salt mixture I	2.5	2.6
Lard	20.0	25.0

Chart XLI (rat 127, male) shows the influence of a diet containing a mixture of isolated foodstuffs in which casein was the sole protein. Period 1 represents the normal growth of the animal on a mixed food. The casein feeding began with period 2. The influence of faeces of normally fed animals in preventing for a time the decline in body-weight is shown during period 3. Period 4 shows the favorable nutritive influence of the substitution of protein-free milk for a part of the non-protein constituents of the diet. The diet during period 1 consisted of mixed food. During periods 2, 3, and 4 the composition of the food was as shown herewith.

Constituents.	Periods 2 and 3.	Constituents.	Per. 4.
	p. ct.		p. ct.
Casein	18.0	Casein	18.0
Starch	32.5	Protein-free milk	28.2
Sugar	21.9 to 26.9	Starch	23.8
Salt mixture I	2.6	Agar	5.0
Lard	20.0 25.0	Lard	25.0

CHART XLI.
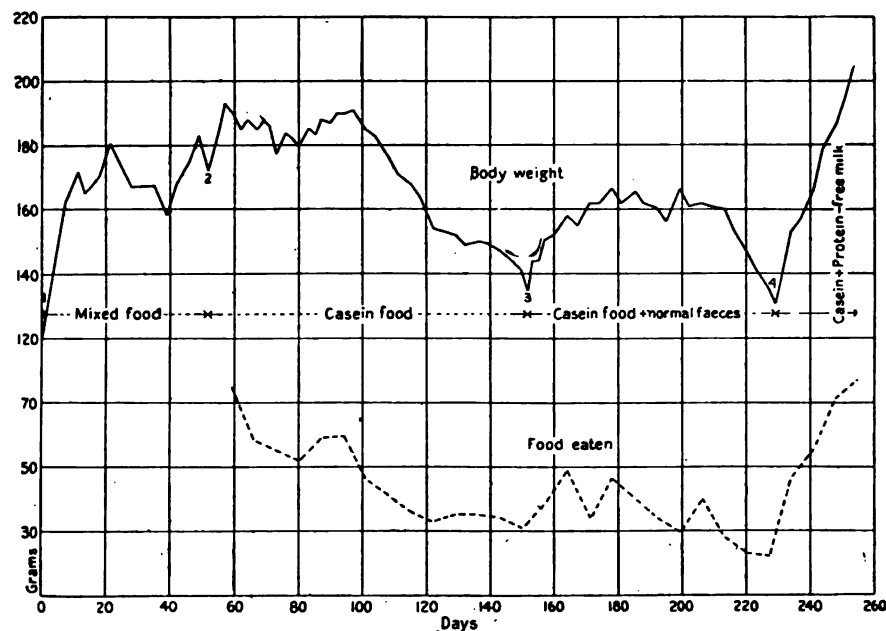
CHART XLII.
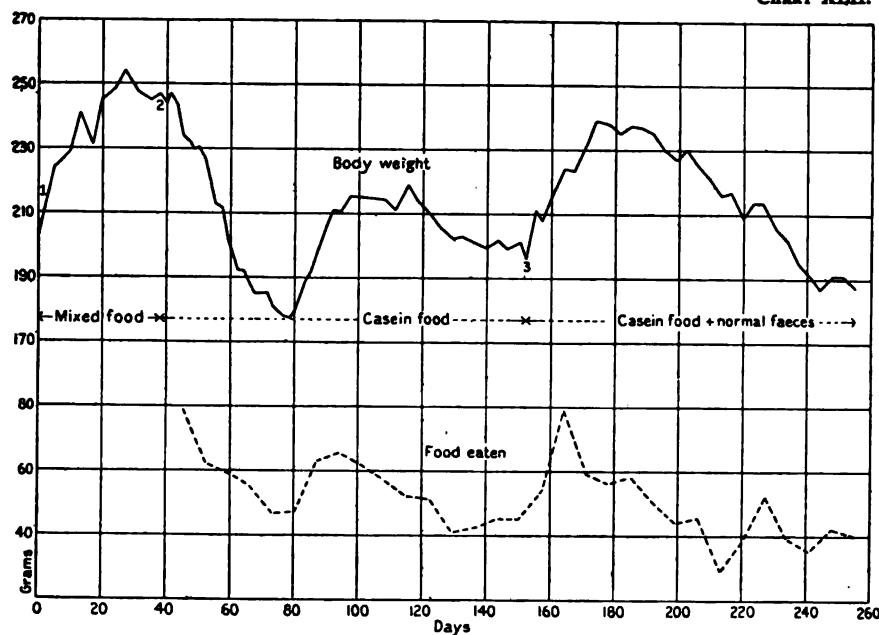
Chart XLII (rat 103, male) shows the influence of a diet of isolated food-stuffs containing casein as the sole protein. The satisfactory previous nutritive condition of the animal is shown during period 1 on mixed food. Casein feeding was begun with period 2; and the favorable effect of fæces of normally fed animals is shown during period 3. The composition of the food in periods 2 and 3 was as shown in table.

	p. ct.	
Casein	18.00	......
Starch	25.00 to	32.50
Sugar	12.87	25.37
Agar	0.00	5.00
Salt mixture	4.13	......
Lard	20.00	35.00

The salt mixture, which was prepared for other purposes, consisted of the citrates of calcium, magnesium, sodium, potassium, and iron, and the chlorides of sodium and potassium.

CHART XLIII.
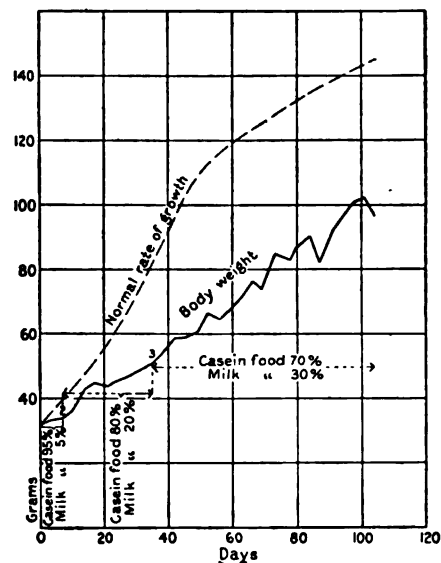
CHART XLIV.
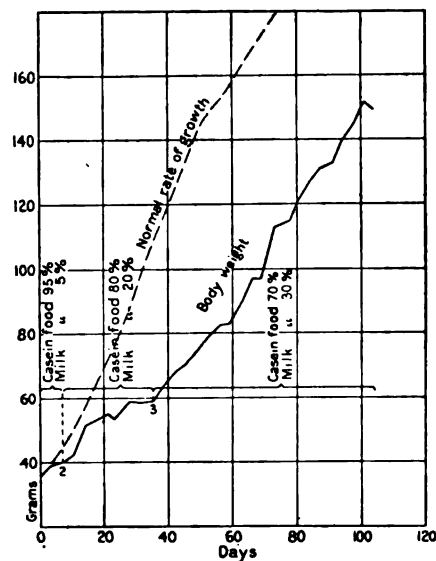
CHART XLV.
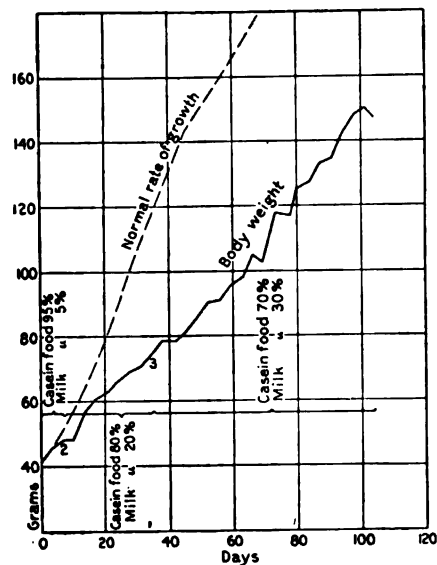
Charts XLIII (rat 231, female), XLIV (rat 230, male), and XLV (rat 223, male) show the effect of successive additions of increasing quantities of milk powder to the usual casein diet. The smaller quantities of milk are insufficient to induce normal growth. The diet during the several periods was as follows:

Constituents.	Per. 1.	Per. 2.	Per. 3.
	p. ct.	p. ct.	p. ct.
*Casein food......	95	80	70
†Milk food.......	5	20	30

* Casein food: casein, 18.0; starch, 32.5; sugar 17.0; agar, 5.0; salt mixture I, 2.5; lard, 25.
†Milk food: Trumilk, 60.0; starch, 15.7; salt mixture I, 1.0; lard, 23.3.

CHART XLVI.
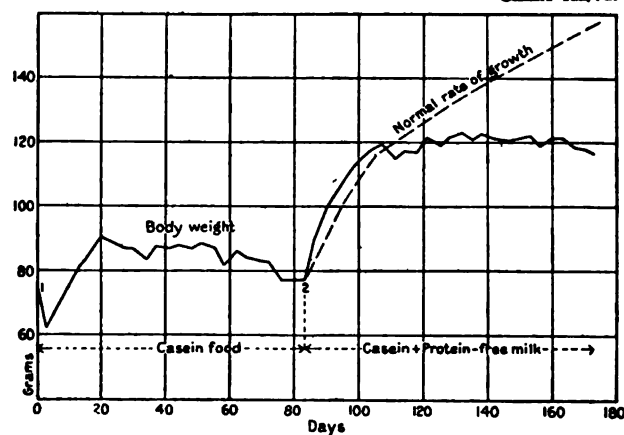
CHART XLVII.
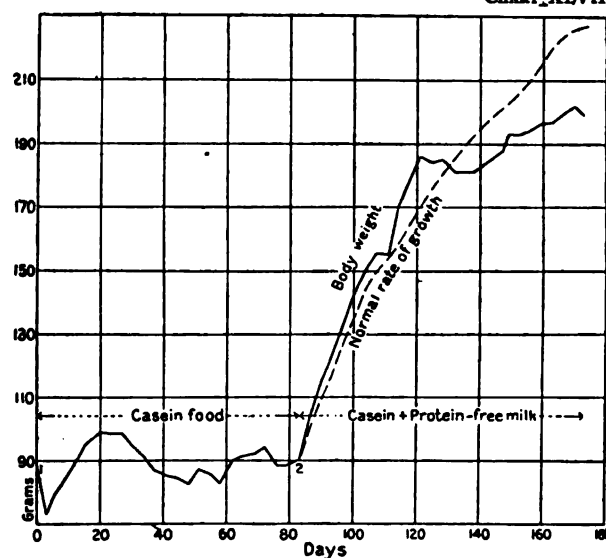
Charts XLVI (rat 177, female) and XLVII (rat 191, male) show maintenance on a diet in which casein formed the sole protein during 83 days followed by growth when protein-free milk was substituted for a part of the non-protein constituents of the diet. The diet was as shown herewith.

Constituents.	Per. 1.	Per. 2.
	p. ct.	*p. ct.*
Casein	18.0	18.0
Protein-free milk	0.0	28.2
Starch	32.5	23.8
Sugar	17.0 to 20.0	0.0
Agar	5.0	5.0
Salt mixture I	2.5	0.0
Lard	22.0 25.0	25.0

CHART XLVIII.
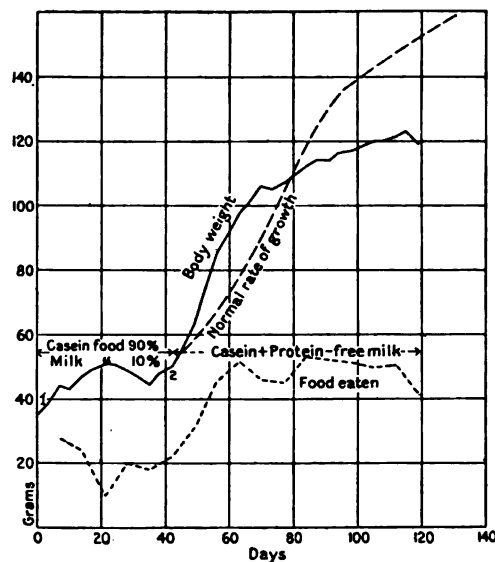
CHART XLIX.
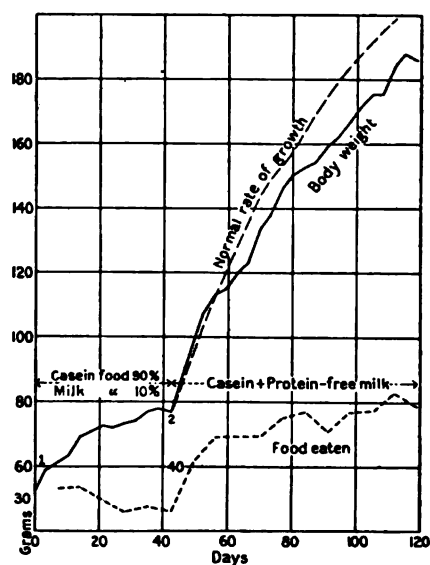
Charts XLVIII (rat 210, female), XLIX (rat 209, male), L (rat 215, male), and LI (rat 216, male) show inadequate growth, during period 1, on the casein food with a small admixture of milk, followed by resumption of growth on a diet containing casein and protein-free milk in a quantity equivalent to that of our milk-paste diet which has proved sufficient to promote normal growth. The composition of the food was as shown in table.

Constituents.	Per. 1.	Constituents.	Per. 2.
	p. ct.		*p. ct.*
Casein food (casein, 18.0; starch, 32.5; sugar, 17.0; agar 5.0; salt mixture I, 2.5; lard, 25.0).........		Casein.......	18.0
		Protein-free	
		milk......	28.2
		Starch......	23.8
	90	Agar........	5.0
Milk food, (Trumilk, 60.0; starch, 15.7; salt mixture I, 1.0; lard, 23.3).........	10	Lard........	25.0

CHART L.

CHART LI.
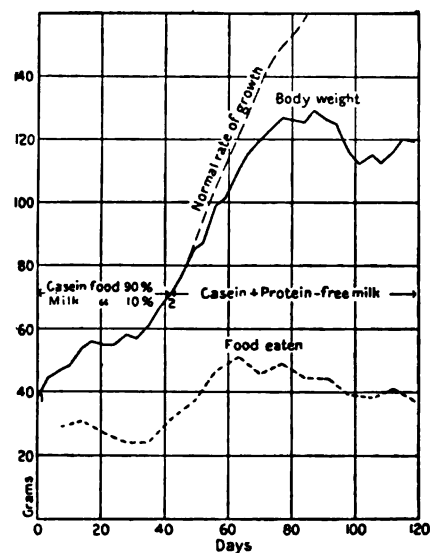
CHART LII.
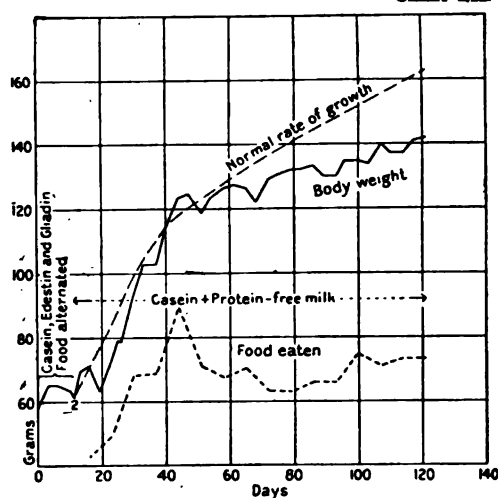
CHART LIII.
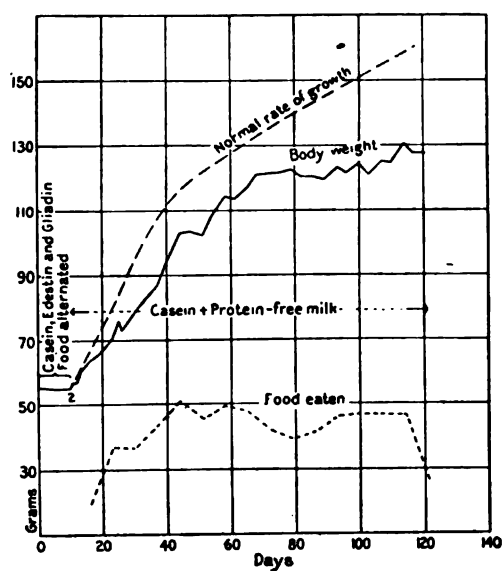
Charts LII (rat 205, female) and LIII (rat 207, female) show initiation of favorable growth when protein-free milk is added to a dietary containing casein as its sole protein in period 2. In the preliminary period an unsuccessful attempt was made to induce growth by feeding different proteins in rotation. The diet was as shown in table.

Constituents.	Per. 1.	Constituents.	Per. 2.
	p. ct.		*p. ct.*
Casein or		Casein............	18.0
Edestin or }...	18.0	Protein-free milk.	28.2
Gliadin		Starch............	23.8
Starch..........	32.5	Agar..............	5.0
Sugar..........	17.0	Lard..............	25.0
Agar...........	5.0		
Salt mixture I...	2.5		
Lard...........	25.0		
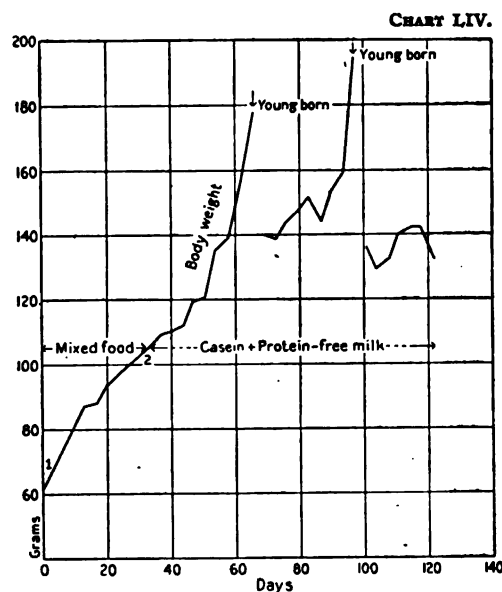
Chart LIV (rat 204, female) shows uninterrupted growth when a diet of isolated food-stuffs containing casein as its sole protein was substituted for mixed food. The requisite inorganic salts were furnished in the added protein-free milk. The experiment is of exceptional interest inasmuch as the animal successfully passed through two periods of pregnancy on a purine-free food containing a single protein. This obviously affords a method of studying various synthetic processes in the animal body. The diet during period 1 consisted of mixed food. During period 2 as shown herewith.

Period 2.	p. ct.
Casein	18.0
Protein-free milk.	28.2
Starch	23.8
Agar	5.0
Lard	25.0

Chart LV (rat 203, male) shows uninterrupted growth when a diet of isolated foodstuffs containing casein as its sole protein was substituted for mixed food. The requisite inorganic salts were furnished in the added protein-free milk. The diet during period 1 consisted of mixed food; during period 2, as shown herewith.
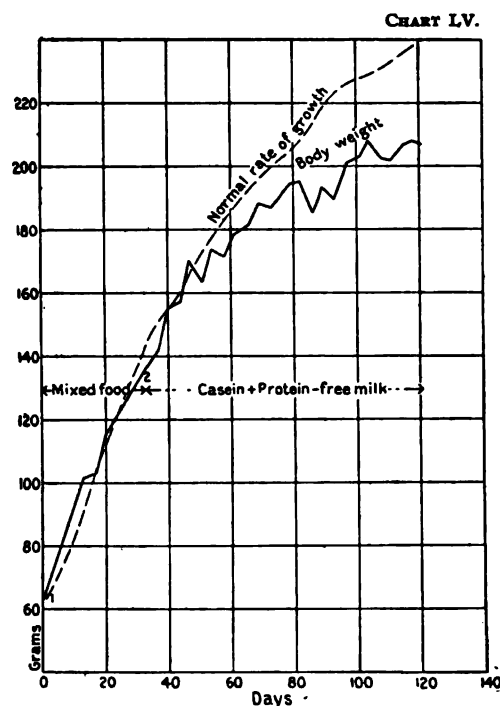
Period 2.	p. ct.
Casein	18.0
Protein-free milk.	28.2
Starch	23.8
Agar	5.0
Lard	25.0
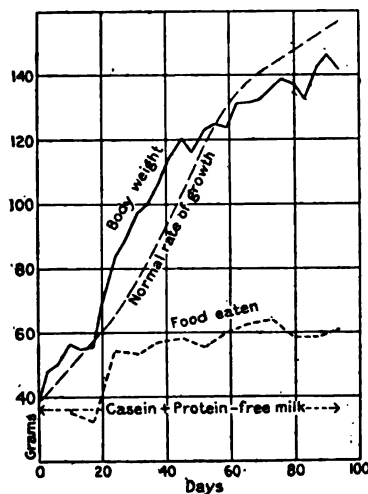
CHART LVI.

CHART LVII.
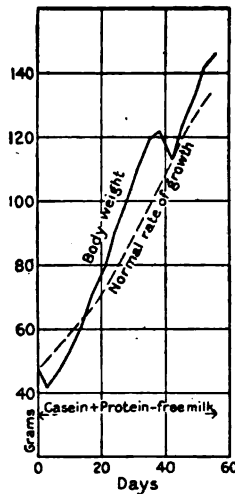
CHART LVIII.
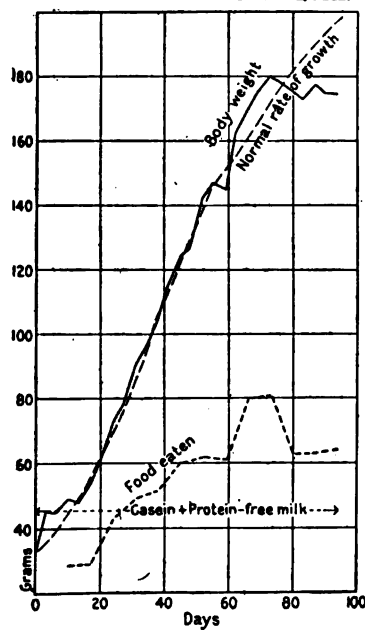
CHART LIX.
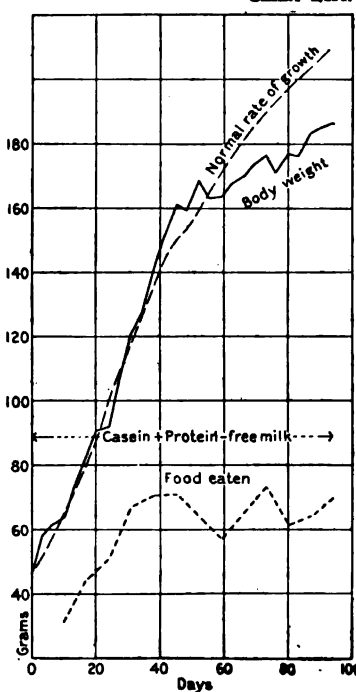
CHART LX.
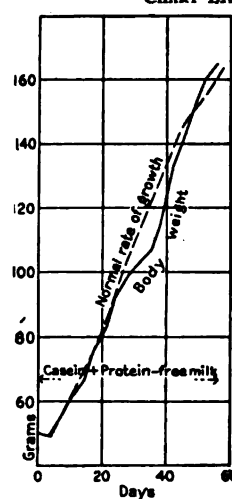
Charts LVI (rat 238, female), LVII (rat 269, female), LVIII (rat 247, male), LIX (rat 252, male), and LX (rat 268, male) show normal growth on a diet containing a single protein, casein. The requisite inorganic salts were furnished in the added protein-free milk. This experiment illustrates artificial nutrition with isolated food-substances from a very early period of life. The diet was as shown herewith.

	p. ct.
Casein	18.0
Protein-free milk	28.2
Starch	23.8
Agar	5.0
Lard	25.0

CHART LXI.

CHART LXII.
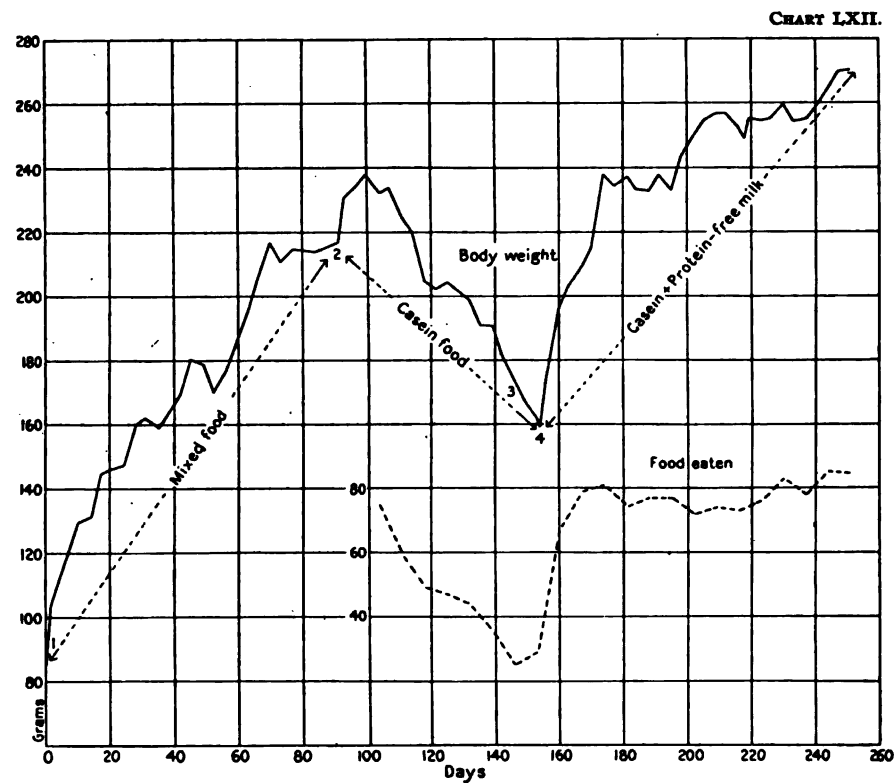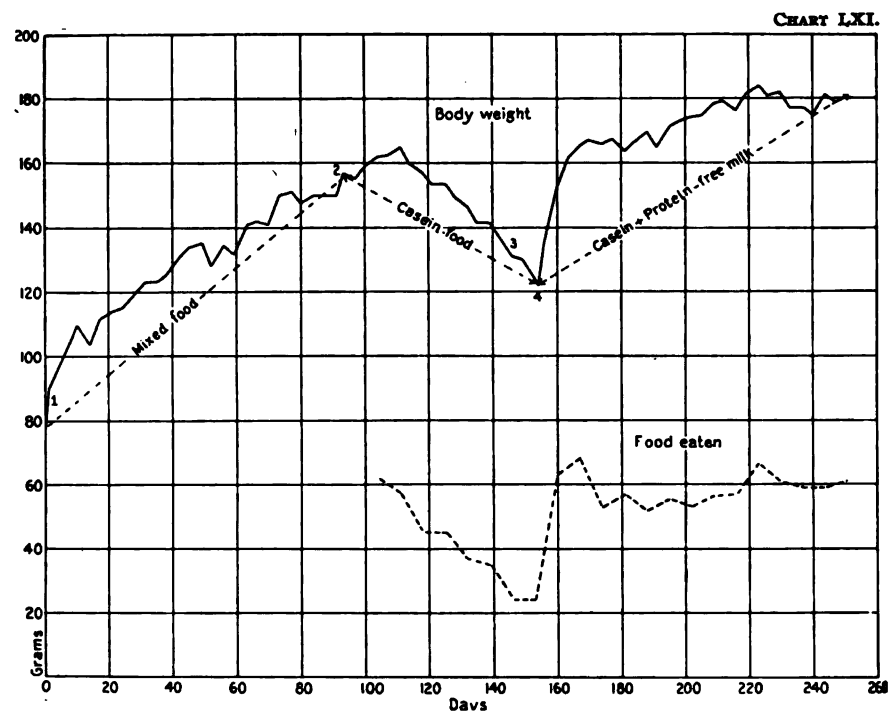
Charts LXI (rat 141, female) and LXII (rat 139, male) show recovery of animals maintained on a diet containing casein as the sole protein. The preliminary nutritive condition of the rats is shown to be satisfactory in period 1 on a mixed diet. The ultimate decline on the casein diet during period 2 could not be checked by increasing the content of casein during period 3. This shows that the nutritive failure of the animals was not attributable to the protein *per se.* Speedy recuperation and maintenance attended the substitution of protein-free milk for the inorganic salt mixture contained in food previously used. Note the influence of this dietary change on the appetite of the animals. In period 1 mixed food was used. The composition of food, during the other periods was as shown in table.

Constituents.	Per. 2.	Per. 3.	Per. 4.
	p. ct.	*p. ct.*	*p. ct.*
Casein............	18.0	36.0	18.0
Protein-free milk	0.0	0.0	28.2
Starch..........	32.5	22.5	23.8
Sugar............	21.9 to 26.9	13.9	0.0
Agar............	0.0 5.0	0.0	5.0
Salt mixture I...	2.5 2.6	2.6	0.0
Lard............	20.0 25.0	25.0	25.0

CHART LXIII.
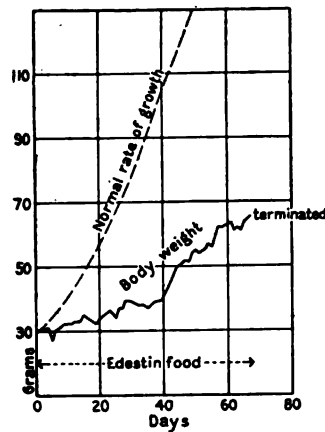
CHART LXIV.
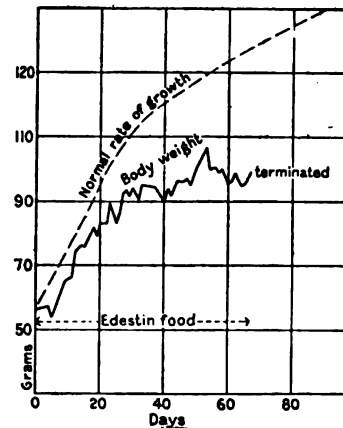
Charts LXIII (rat 60, male) and LXIV (rat 58, female) show maintenance and slight growth of a rat on a diet in which edestin constituted the sole protein for 67 days. The experiment was terminated because of the death of another animal, which was found partly eaten, in the same cage. The diet was as shown herewith.

p. ct.
Edestin...... 18.0
Starch........ 29.5
Sugar........ 15.0
Agar......... 5.0
Salt mixture I. 2.5
Lard......... 30.0

CHART LXV.
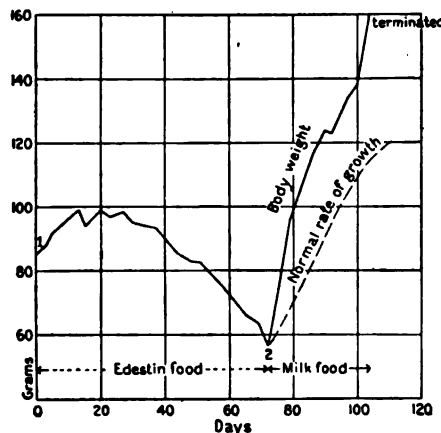
Chart LXV (rat 189, female) shows failure of rat to grow or be maintained on a diet containing edestin as the sole protein during 72 days (period 1). There is no loss of capacity to grow, as will be seen by the curve of growth on the milk diet in period 2, 32 days. The diet consisted of—

Period 1.	*p. ct.*
Edestin........................	18.0
Starch........................	29.5
Sugar........................	15.0
Agar.........................	5.0
Salt mixture I................	2.5
Lard.........................	30.0

Period 2.	
Trumilk......................	60.0
Starch.......................	15.7
Salt mixture I................	1.0
Lard.........................	23.3

CHART LXVI.
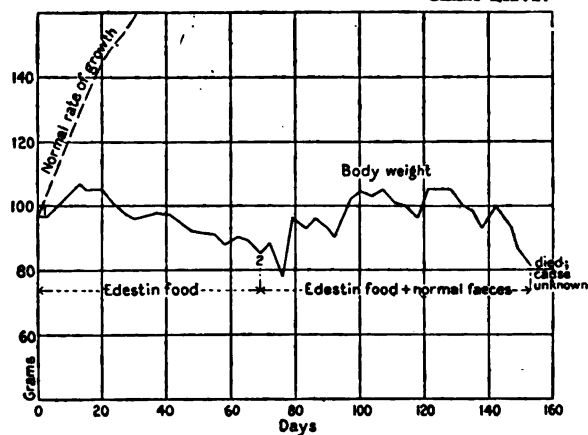
Charts LXVI (rat 169, male) and LXVII (rat 190, male) show maintenance on a diet in which edestin formed the sole protein. The influence of fæces of normally fed animals in preventing decline in body-weight for some time is shown during period 2. The fæces were obtained from rats temporarily introduced into the cage each day. The diet is given above.

	p. ct.	
Edestin..........	18.0	....
Starch..........	29.5 to 32.5	
Sugar..........	15.0	17.0
Agar..........	5.0	....
Salt mixture, I...	2.5	....
Lard..........	25.0	30.0

CHART LXVII.
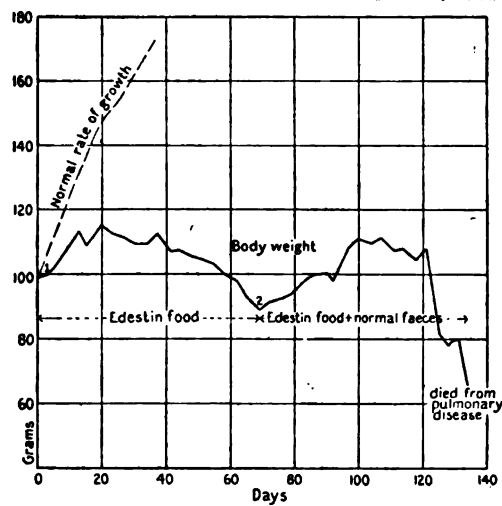
CHART LXVIII.
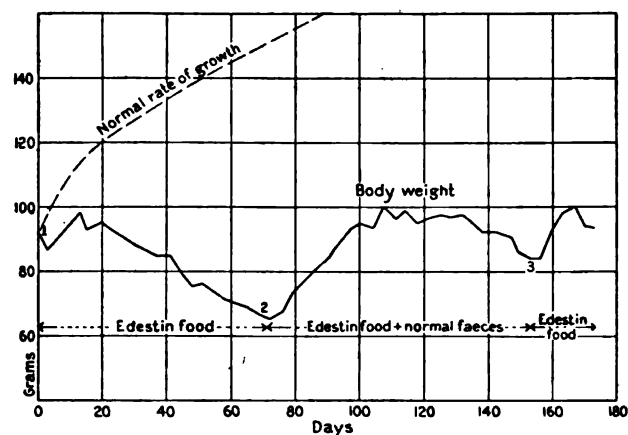
Charts LXVIII (rat 196, female) and LXIX (rat 193, female) show maintenance on a diet in which edestin formed the sole protein. The influence of fæces of normally fed animals in preventing decline in body-weight is shown during period 2. The giving of fæces was discontinued during period 3. The fæces were obtained from normally fed rats temporarily introduced into the cage each day. The diet is given above.

	p. ct.	
Edestin.........	18.0	....
Starch..........	29.5 to 32.5	
Sugar...........	15.0	17.0
Agar...........	5.0	....
Salt mixture I....	2.5	....
Lard...........	25.0	30.0

CHART LXIX.
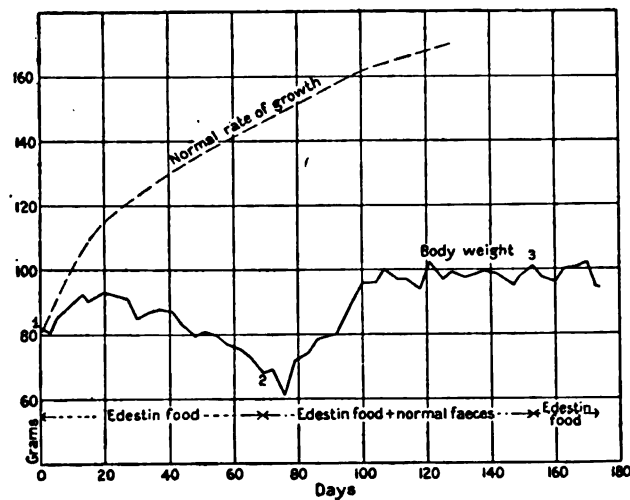
CHART LXX.
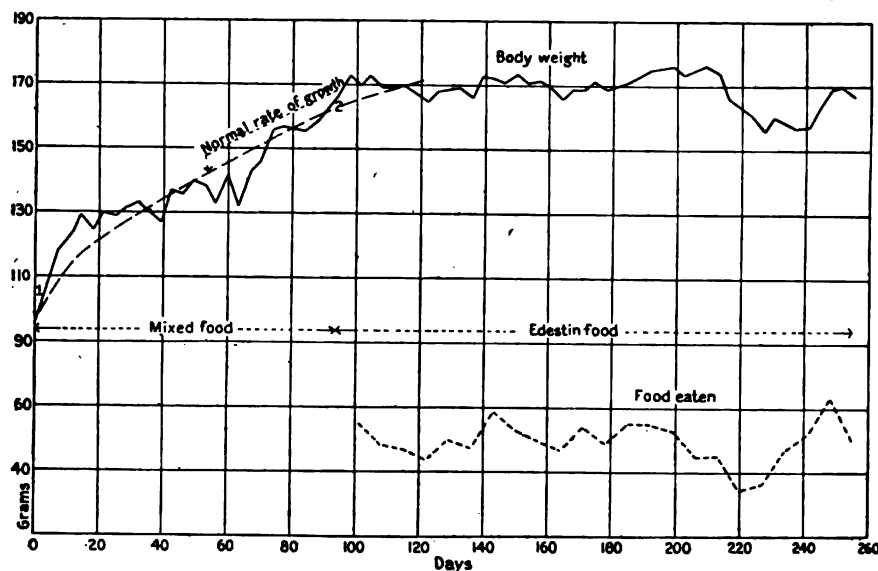
Chart LXX (rat 133, female) shows maintenance on a diet in which edestin was the sole protein during 161 days. Period 1 on a mixed diet shows normal growth. Period 2 is of interest because the food was also purine-free and devoid of organically combined phosphorus. All growth ceased during the edestin feeding (period 2), in contrast with other experiences where protein-free milk was present in the dietary.

Period 2.		
	p. ct.	
Edestin..........	18.0	....
Starch..........	29.5 *to* 32.5	
Sugar..........	15.0	17.0
Agar..........	5.0	....
Salt mixture I....	2.5	....
Lard..........	25.0	30.0

Chart LXXI (rat 218, female) shows inadequate growth on a diet of edestin + milk-paste (period 1) followed by growth during period 2, in which the food contained protein-free milk and edestin as its sole protein. In growing to several times its original weight the animal must have synthesized its purine- and phosphorus-containing complexes from purine-free food. The influence of size on food requirement is shown by the food-intake curve. The diet consisted of—
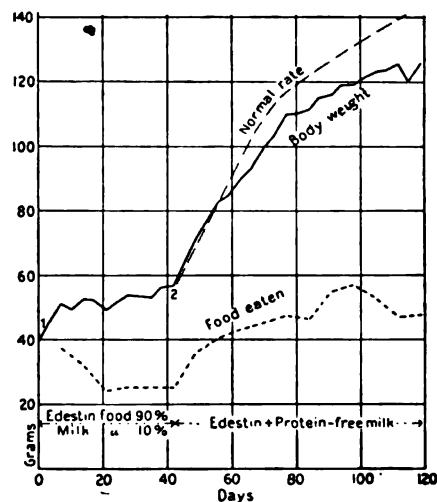
CHART LXXI.

Period 1.	*p. ct.*
Edestin food (edestin, 18.0; starch, 32.5; sugar, 17.0; agar, 5.0; salt mixture I, 2.5; lard, 25.0)............	90
Milk food (Trumilk, 60.0; starch 15.7; salt mixture I, 1.0; lard, 23.3.)....	10

Period 2.	
Edestin	18.0
Protein-free milk	28.2
Starch	23.8
Agar	5.0
Lard	25.0

CHART LXXII.
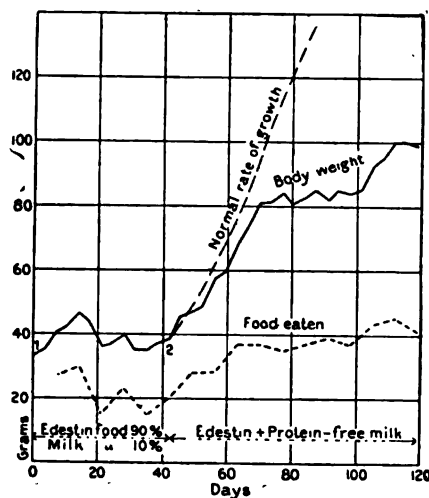
CHART LXXIV.
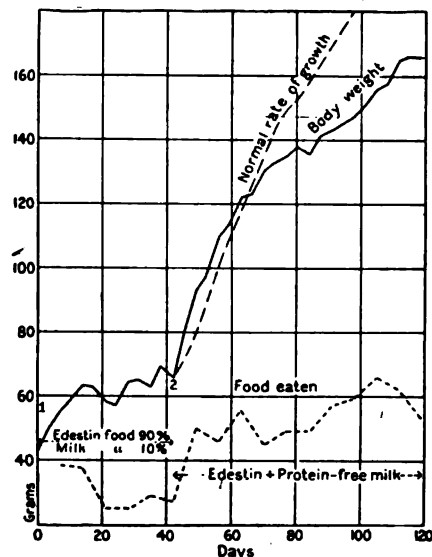
CHART LXXIII.
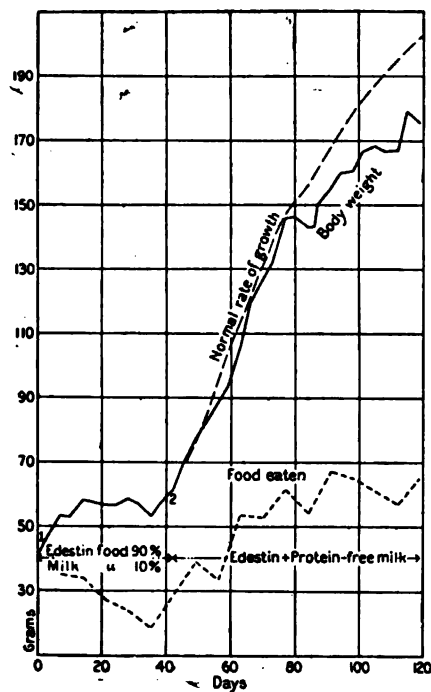
Charts LXXII (rat 217, male), LXXIII (rat 211, male), and LXXIV (rat 212, male) show inadequate growth on a diet of edestin+milk-paste (period 1) followed by growth during period 2, in which the food contained protein-free milk and edestin as its sole protein. It should be noted that the animals in growing to several times their original weight must have synthesized their purine-and phosphorus-containing complexes from purine-free food. The influence of size on the food requirement is shown by the food intake curve. The diet consisted of—

	p. ct.
Period 1.	
Edestin food (edestin, 18.0; starch, 32.5; sugar, 17.0; agar, 5.0; salt mixture I, 2.5; lard, 25.0)	90.0
Milk food (Tramilk, 60.0; starch; 15.7, salt mixture I, 1.0; lard,, 23.3)	10.0
Period 2.	
Edestin	18.0
Protein-free milk	28.2
Starch	23.8
Agar	5.0
Lard	25.0

CHART LXXV.   CHART LXXVI.
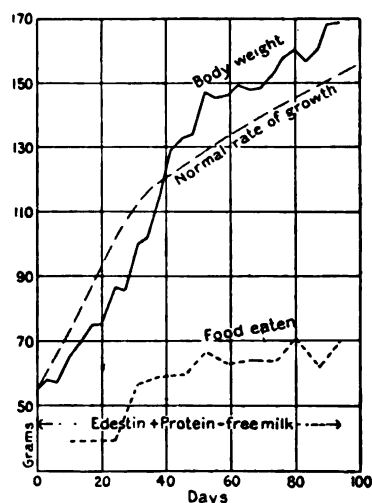
Charts LXXV (rat 248, female) and LXXVI (rat 253, female) show growth from an early age on a diet containing protein-free milk in which edestin formed the sole protein. It should be noted that the animals in growing to several times their original weight must have

p. ct.
Edestin.......... 18.0
Protein-free milk. 28.2
Starch.......... 23.8
Agar............ 5.0
Lard............ 25.0

synthesized their purine- and phosphorus-containing complexes from purine-free food. The influence of size on the food requirement is shown by the food-intake curve. The diet was as shown herewith.

Chart LXXVII (rat 114, male) shows the failure of edestin (period 2) to maintain previous satisfactory nutritive condition of the animal during period 1, on mixed food, even after adding fæces to the diet (period 3). Immediate improvement and satisfactory nutritive condition followed addition of protein-free milk to edestin food (period 4). The diet consisted of mixed food for period 1, and for periods 2, 3, and 4 was as shown in table.

Constituents.	Periods 2 and 3.		Constituents.	Per. 4.
	p. ct.			*p. ct.*
Edestin..........	18.0	.....	Edestin..........	18.0
Starch..........	29.5 to 32.5		Protein-free milk....	28.2
Sugar..........	15.0	17.0	Starch..........	23.8
Agar..........	5.0	.....	Agar..........	5.0
Salt mixture I....	2.5	.....	Lard..........	25.0
Lard..........	25.0	30.0		

Chart LXXVIII (rat 140, female) shows the failure of maintenance on a diet in which edestin formed the sole protein (period 2), until protein-free milk was added to the diet (period 3). Period 1, on mixed food, is introduced to show the previous satisfactory nutritive condition of the animal. The diet consisted of mixed food for period 1, and for periods 2 and 3 it was as shown in table.

| Constituents.	Per. 2.		Per. 3.
	p. ct.		*p. ct.*
Edestin..........	18.0	.....	18.0
Protein-free milk....	0.0	.....	28.2
Starch..........	29.5 to 32.5		23.8
Sugar..........	15.0	17.0	0.0
Agar..........	5.0	.....	5.0
Salt mixture I.......	2.5	.....	0.0
Lard..........	25.0	30.0	25.0

Chart LXXVII.
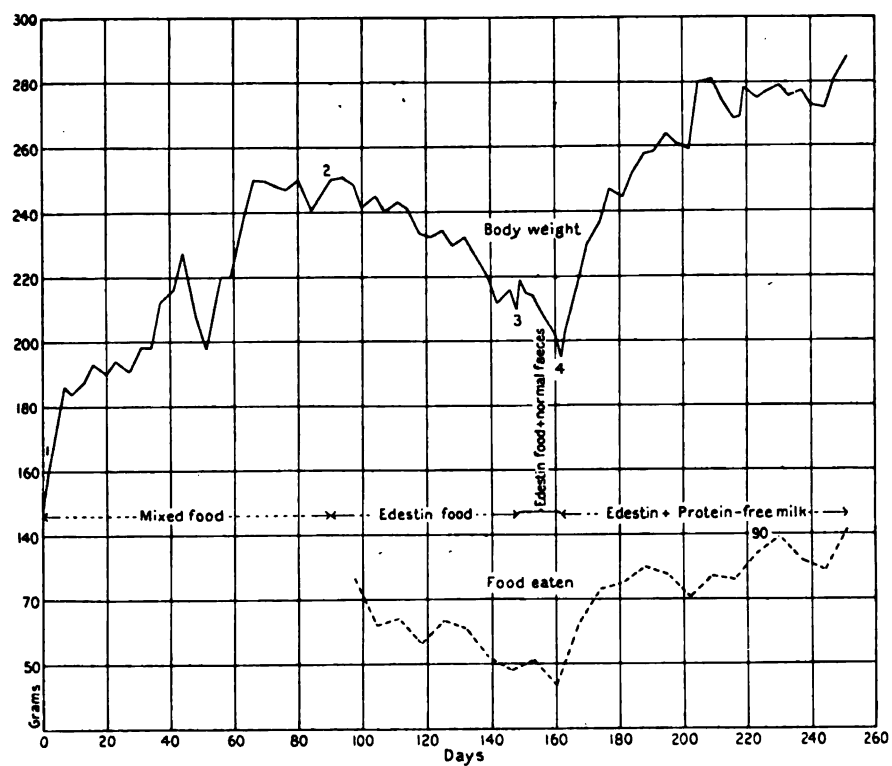
Chart LXXVIII.
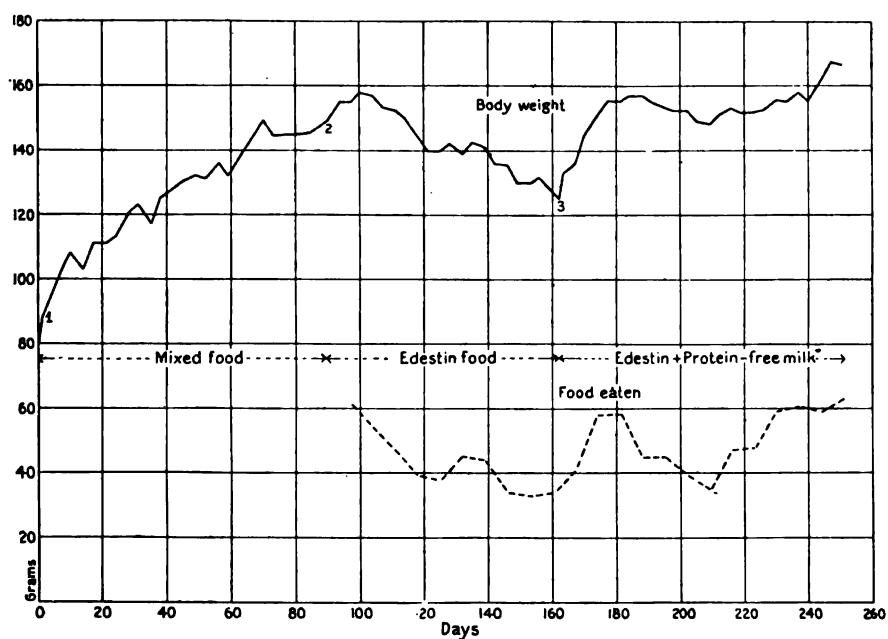
CHART LXXIX.
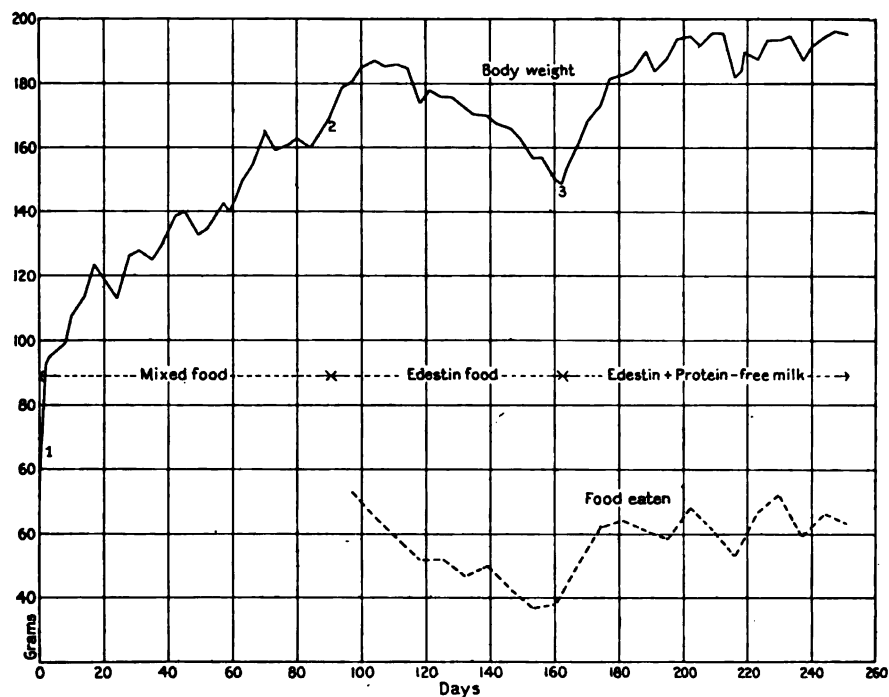
Chart LXXIX (rat 152, female) shows the failure of maintenance on a diet in which edestin formed the sole protein (period 2), until protein-free milk was added to the diet (period 3). Period 1, on mixed food, is introduced to show the previous satisfactory nutritive condition of the animal. The diet consisted of mixed food for period 1 and for periods 2 and 3 was as follows:

Constituents.	Per. 2.	Per. 3.
	p. ct.	*p. ct.*
Edestin...............	18.0	18.0
Protein-free milk....	0.0	28.2
Starch...............	29.5 to 32.5	23.8
Sugar................	15.0 17.0	0.0
Agar.................	5.0	5.0
Salt mixture I........	2.5	0.0
Lard.................	25.0 30.0	25.0

CHART LXXX.

Chart LXXX (rat 148, male) shows the failure of maintenance on a diet in which edestin formed the sole protein (period 2), until protein-free milk was added to the diet (period 3). Period 1, on mixed food, is introduced to show the previous satisfactory nutritive condition of the animal. Note the influence of changes in diet on the food consumption. The diet consisted of mixed food for period 1, and for periods 2 and 3 was as follows:

Constituents.	Per. 2.	Per. 3.
	p. ct.	*p. ct.*
Edestin.............	18.0	18.0
Protein-free milk....	0.0	28.2
Starch..............	29.5 to 32.5	23.8
Sugar...............	15.0 17.0	0.0
Agar................	5.0	5.0
Salt mixture I........	2.5	0.0
Lard................	25.0 30.0	25.0

CHART LXXXI.
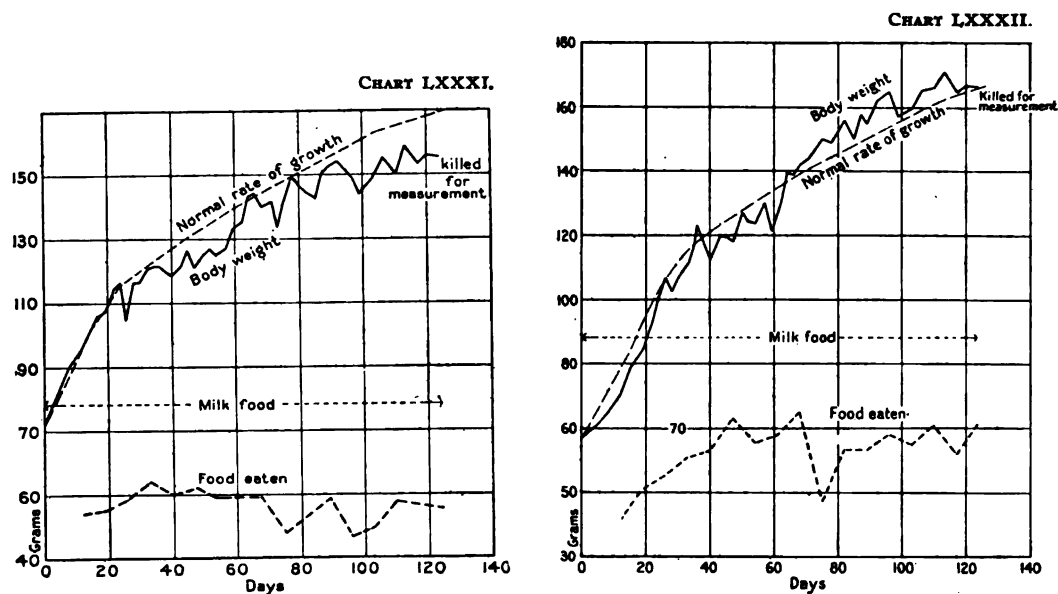
CHART LXXXII.

Charts LXXXI (rat 96, female) and LXXXII (rat 97, female). Control animals for the glutenin dwarfs, Charts LXXXIV–LXXXVI. For other data see page 73. The diet consisted of Trumilk, 60 p. ct.; starch, 15.7 p. ct.; salt mixture I, 1 p. ct., lard, 23.3 p. ct.
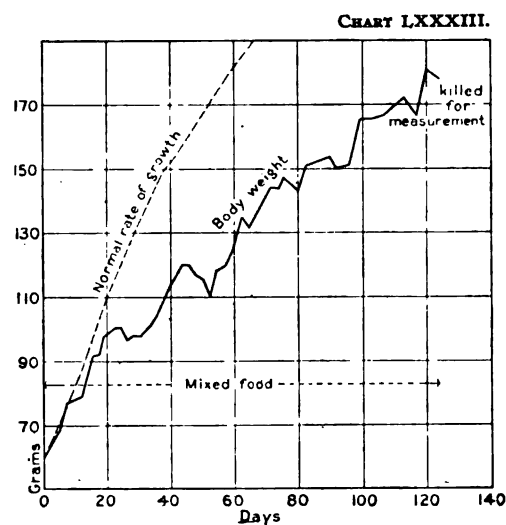
CHART LXXXIII.

Chart LXXXIII (rat 99, male). Control animal for the glutenin dwarfs, Charts LXXXIV–LXXXVI. For other data see page 73. The diet consisted of mixed food.

CHART LXXXIV.
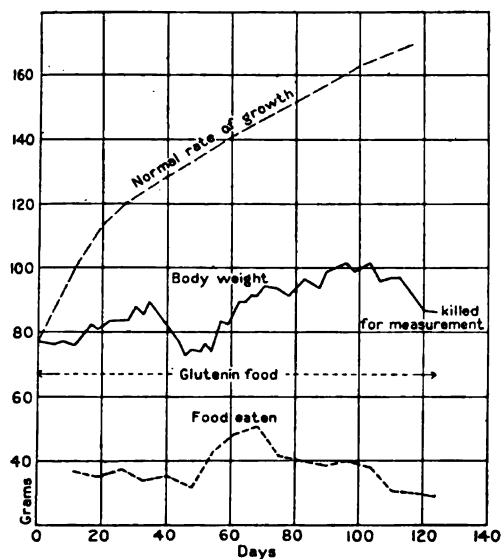
CHART LXXXV.
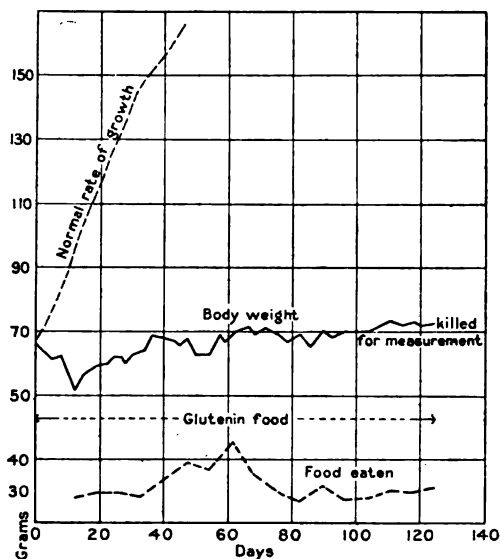
CHART LXXXVI.
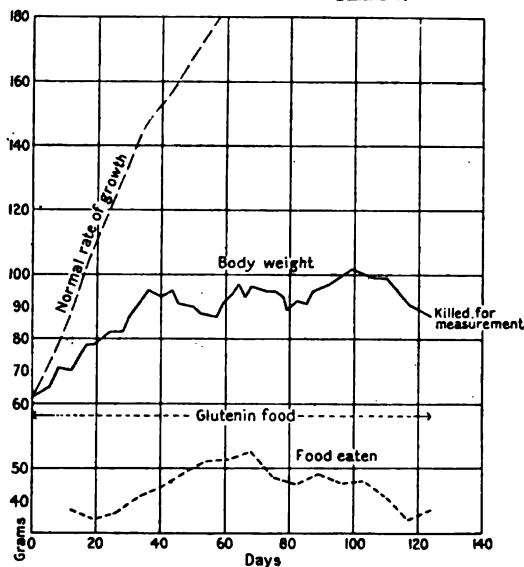
Charts LXXXIV (rat 100, female), LXXXV (rat 101, male), and LXXXVI (rat 102, male). These animals, from the same family as the control rats, Charts LXXXI–LXXXIII, were maintained on a diet of glutenin from wheat 124 days, when they were killed for measurement. The chart illustrates maintenance without appreciable growth. For other data see page 73. The diet was as shown herewith.

	p. ct.	
Glutenin..........	18.0	....
Starch...........	14.5 to 34.5	
Sugar...........	15.0	20.0
Agar............	5.0	....
Salt mixture I....	2.5	....
Lard...........	20.0	45.0
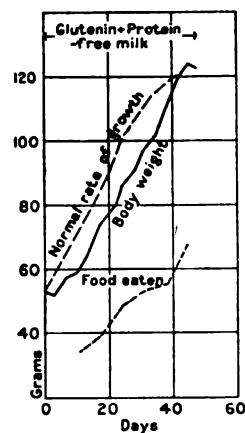
CHART LXXXVII.   CHART LXXXVIII.   CHART LXXXIX.
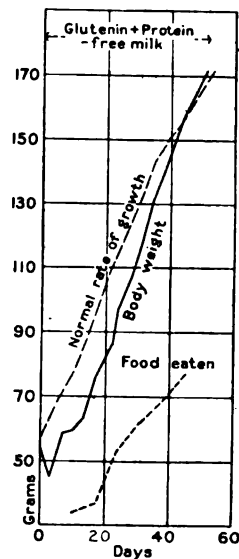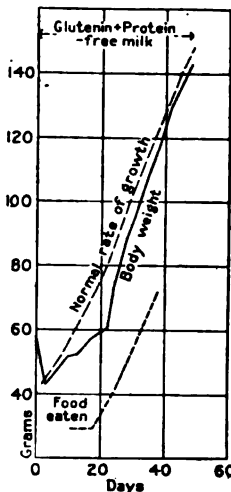
Charts LXXXVII (rat 293, female), LXXXVIII (rat 284, male), and LXXXIX (rat 279, male) show growth from an early age on a diet containing protein-free milk, in which glutenin from wheat formed the sole protein. The animals in growing to several times their original weight must have synthesized their purine- and phosphorus-containing complexes from purine-free food. The influence of size on the food requirement is shown by the food-intake curves. The diet was as shown in table.

	p. ct.
Glutenin	18.0
Protein-free milk	28.2
Starch	23.8
Agar	5.0
Lard	25.0
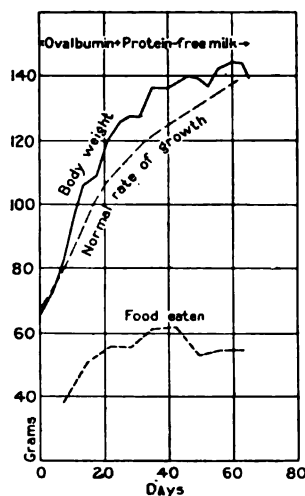
CHART XC.   CHART XCI.
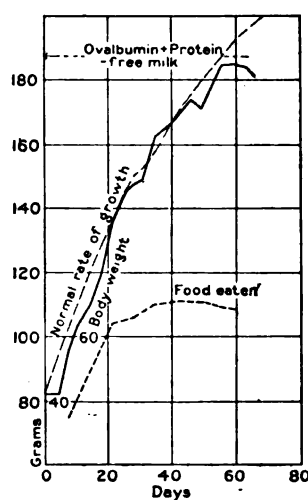
Charts XC (rat 258, female) and XCI (rat 250, male) show growth from an early age on a diet containing protein-free milk, in which ovalbumin formed the sole protein. The animals in growing to several times their original weight must have synthesized their purine-containing complexes from purine-free food. The influence of size on food requirement is shown by the food-intake curves. The diet was as shown above.

	p. ct.
Ovalbumin	18.0
Protein-free milk	28.2
Starch	23.8
Agar	5.0
Lard	25.0

CHART XCII.
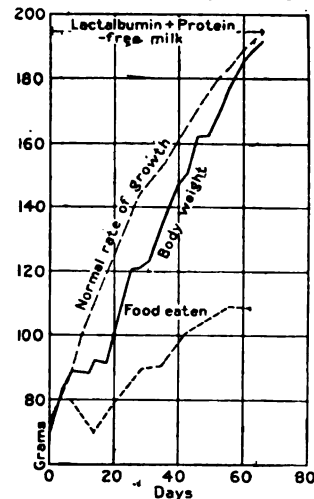
CHART XCIII.
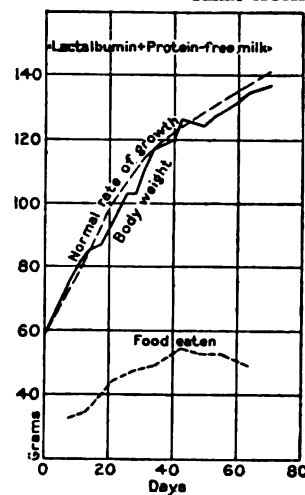
Charts XCII (rat 251, male) and XCIII (rat 259, female) show growth from an early age on a diet containing protein-free milk, in which lactalbumin formed the sole protein. The animals in growing to several times their original weight must have synthesized their purine- and phosphorus-containing complexes from purine-free food. The influence of size on the food requirement is shown by the food-intake curves. The diet was as shown herewith.

	p. ct.	
Lactalbumin....	18.0	....
Protein-free milk.	28.2	....
Starch...........	16.8 to 18.8	
Agar...........	5.0	....
Lard...........	30.0	32.0

CHART XCIV.
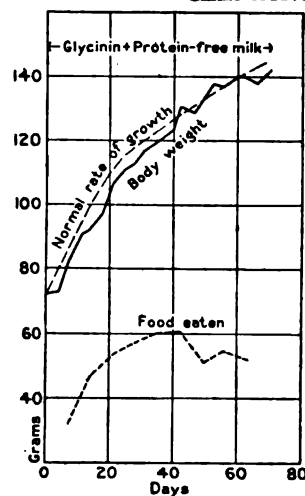
CHART XCV.
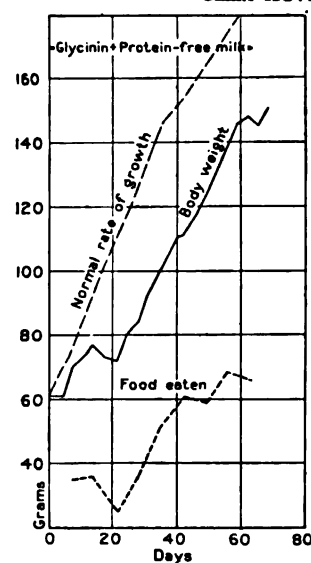
Charts XCIV (rat 257, female) and XCV (rat 241, male) show growth from an early age on a diet containing protein-free milk, in which glycinin formed the sole protein. The animals in growing to several times their original weight must have synthesized their purine-containing complexes from purine-free food. The influence of size on food requirement is shown by the food-intake curves. The diet was as shown herewith.

	p. ct.
Glycinin..........	18.0
Protein-free milk.	28.2
Starch...........	23.8
Agar.............	5.0
Lard.............	25.0

CHART XCVI.
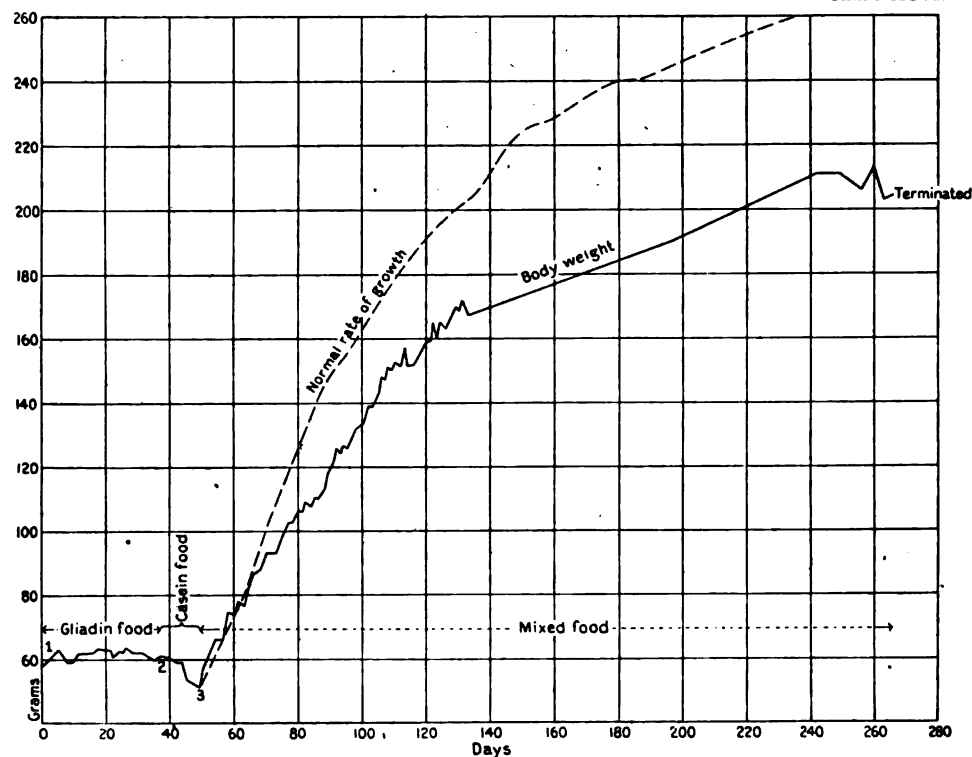
Chart XCVI (rat 36, male) shows the failure of inhibition of growth to check the "capacity to grow." The rat was stunted on gliadin food for 37 days (period 1) and on casein food for 12 days (period 2) and completely recovered growth on mixed diet during 217 days (period 3). The diet for periods 1 and 2 was as follows:

Constituents.	Per. 1.	Constituents.	Per. 2.
	p. ct.		*p. ct.*
Gliadin (from wheat)...	18.0	Casein...........	18.0
Starch.................	29.5	Starch..........	29.5
Sugar.................	15.0	Sugar...........	15.0
Agar...................	5.0	Agar............	5.0
Salt mixture I..........	2.5	Salt mixture I...	2.5
Lard....................	30.0	Lard............	30.0

Chart XCVII (rat 37, male) shows unimpaired capacity for growth on mixed diet and milk diet after an earlier period of stunted growth on gliadin diet for 37 days (period 1) and casein diet for 12 days (period 2). Part of the period of growth was accomplished on milk food, part on mixed food, the change being made at 3 to mixed food, at 4 to milk food, and at 5 to

mixed food again. Note that this has not affected the typical character of the curve of growth. The diet was as follows:

Constituents.	Per. 1.	Constituents.	Per. 2.	Periods 3 and 5.	Constituents.	Per. 4.
	p. ct.		p. ct.			p. ct.
Gliadin (from wheat)...	18.0	Casein...........	18.0	Mixed	Trumilk....	60.0
Starch..................	29.5	Starch...........	29.5	food.	Starch......	16.7
Sugar...................	15.0	Sugar............	15.0		Lard........	23.3
Agar....................	5.0	Agar.............	5.0			
Salt mixture I..........	2.5	Salt mixture I...	2.5			
Lard....................	30.0	Lard.............	30.0			
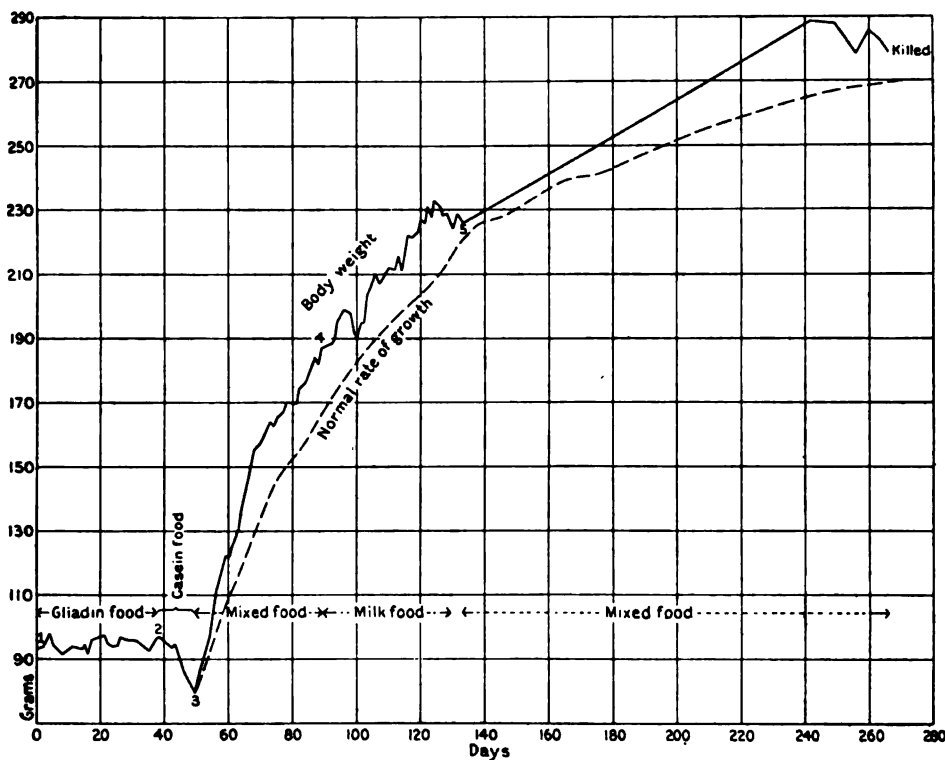
CHART XCVII.

CHART XCVIII.
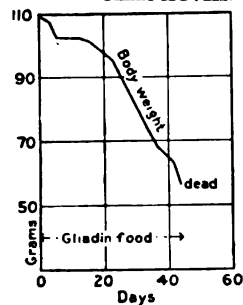
Chart XCVIII (rat 185, male) shows the failure of a rat to be maintained on a diet composed as shown herewith.

	p. ct.
Gliadin (from wheat)...	18.0
Starch..................	29.5
Sugar...................	15.0
Agar....................	5.0
Salt mixture I..........	2.5
Lard....................	30.0
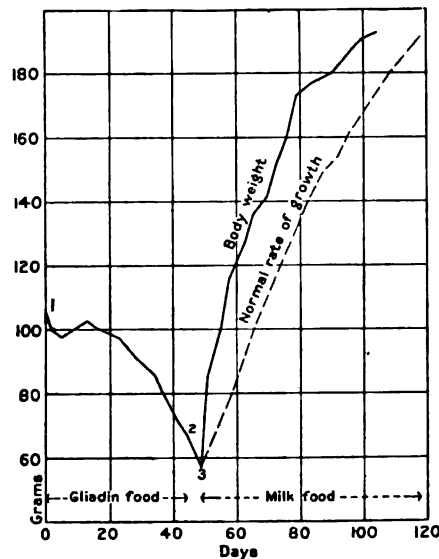
CHART XCIX.   CHART C.
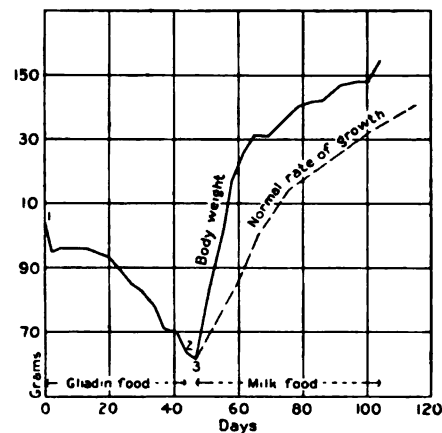
Charts XCIX (rat 186, male) and C (rat 188, female) show the failure of the rat to be maintained during periods 1 and 2 on diets mentioned below. The perfect resumption of growth when the diet consisted of milk-paste (period 3) illustrates that the "capacity to grow" normally is not visibly impaired by previous large loss of body-weight. The food consisted of—

Constituents.	Per. 1.	Per. 2.	Constituents.	Per. 3.
	p. ct.	p. ct.		p. ct.
Gliadin (from wheat)...	18.0	0.0	Trumilk...........	60.0
Edestin.................	0.0	18.0	Starch............	15.7
Starch.................	29.5	32.5	Salt mixture I....	1.0
Sugar..................	15.0	17.0	Lard.............	23.3
Agar...................	5.0	5.0		
Salt mixture I..........	2.5	2.5		
Lard...................	30.0	25.0		

Chart CI (rat 147, female). The animal, well nourished on a mixed diet during period 1, failed to maintain its body-weight on a diet in which gliadin was the sole protein (period 2), until fæces were added in period 3. The diet consisted of mixed food during period 1; for periods 2 and 3 it was as shown herewith.

	p. ct.	
Gliadin (from wheat).	18.0	....
Starch...............	29.5 to	34.5
Sugar................	15.0	17.0
Agar.................	5.0	....
Salt mixture I.......	2.5	....
Lard.................	25.0	30.0

Chart CII (rat 142, female). The animal, well nourished on a mixed diet during period 1, failed to maintain its body-weight on a diet in which gliadin was the sole protein (period 2). The addition of fæces to the diet in periods 3 and 4 checked the decline. During period 3 the fæces added were thoroughly sterilized and seemed to be less efficient than the unsterilized fæces in period 4, or in other similar experiments. The diet consisted of mixed food during period 1; for periods 2, 3, and 4 it was as shown herewith.

	p. ct.	
Gliadin (from wheat).	18.0	....
Starch...............	29.5 to	34.5
Sugar................	15.0	17.0
Agar.................	5.0	....
Salt mixture I.......	2.5	....
Lard.................	25.0	30.0
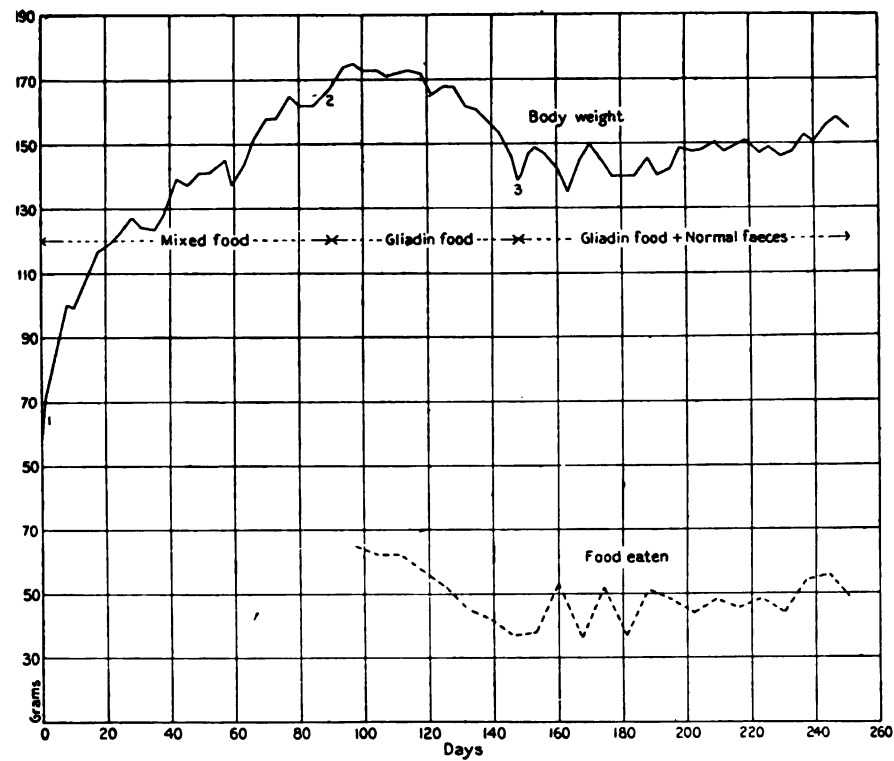
CHART CI.

CHART CII.
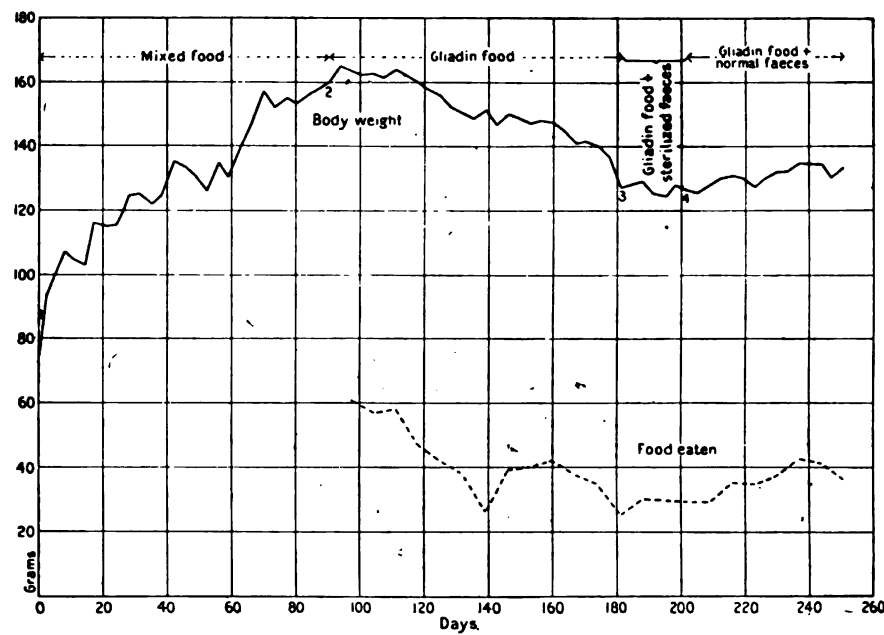
CHART CIII.
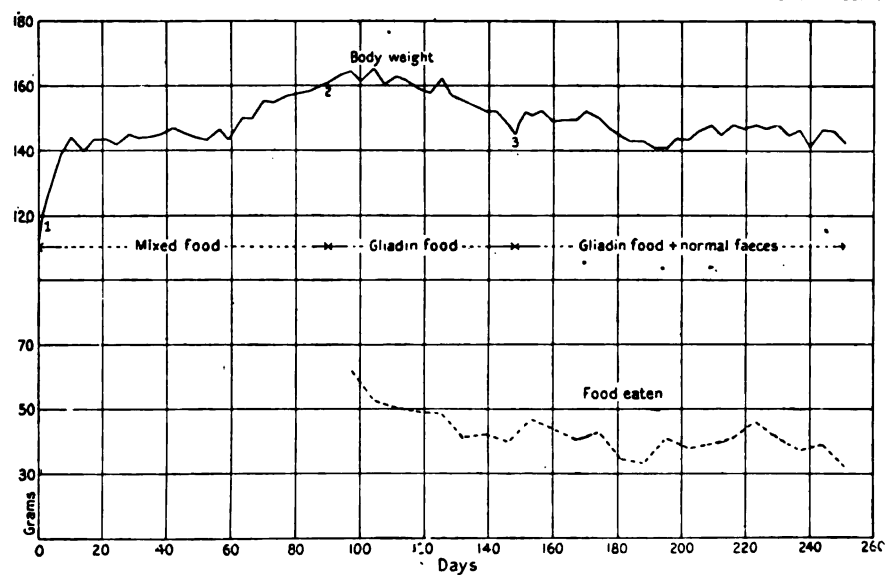
Chart CIII (rat 130, female). The animal, well nourished on a mixed diet during period 1, failed to maintain its body-weight on a diet in which gliadin was the sole protein (period 2), until fæces were added in period 3. The diet consisted of mixed food during period 1; for periods 2 and 3 it was as shown.

	p. ct.	
Gliadin (from wheat).	18.0	....
Starch	29.5 to 34.5	
Sugar	15.0	17.0
Agar	5.0	....
Salt mixture I	2.5	....
Lard	25.0	30.0
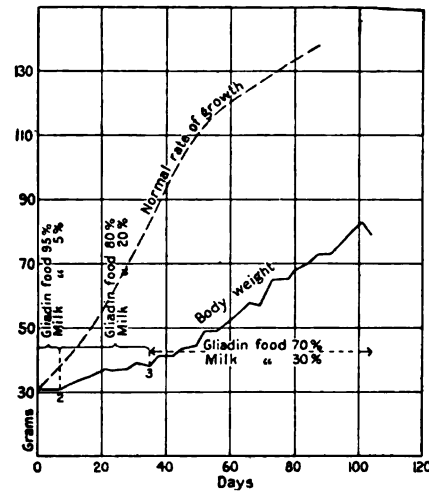
CHART CIV.

CHART CV.
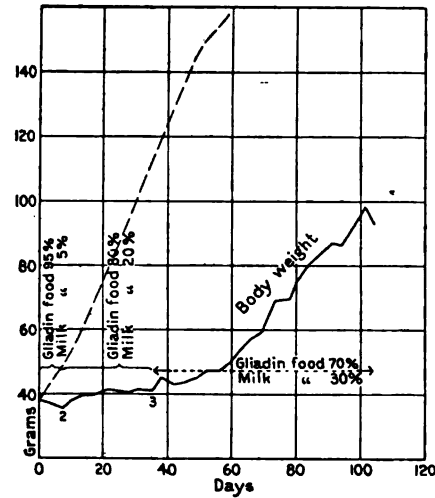
CHART CVI.
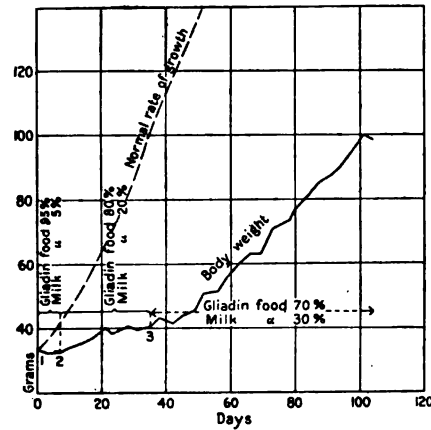
CHART CVII.
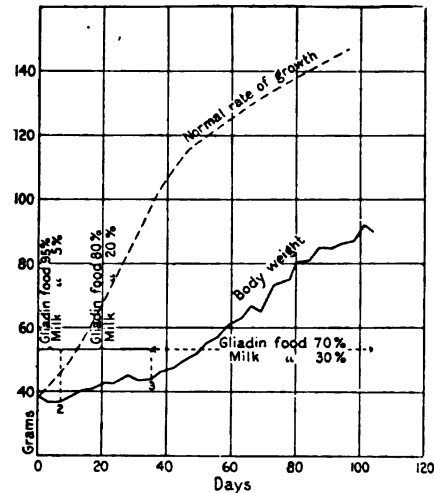
Charts CIV (rat 234, female), CV (rat 228, female), CVI (rat 235, male), and CVII (rat 227, male) show the effect of successively larger additions of milk-paste to gliadin food mixture which has been shown in other experiments to be inadequate for the purposes of growth. Note the more rapid growth as the content of milk is increased. The diet consisted of—

Constituents.	Per. 1.	Per. 2.	Per. 3.
	p. ct.	p. ct.	p. ct.
*Gliadin food.....	95	80	70
†Milk food.......	5	20	30

*Gliadin food: gliadin (from wheat) 18.0; starch, 29.5 to 32.5; sugar, 17.0; agar, 5.0; salt mixture I, 2.5; lard, 25 to 28.
†Milk food: Trumilk, 60.0; starch, 15.7; salt mixture I, 1.0; lard, 23.3.

CHART CVIII.
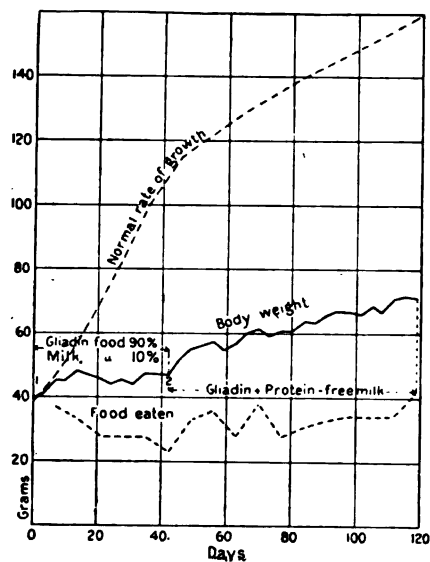
CHART CIX.
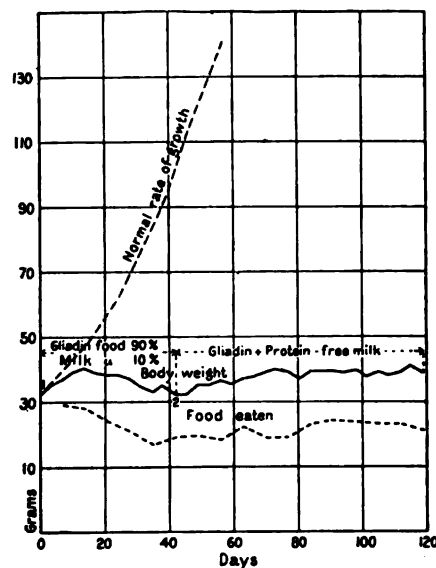
CHART CX.
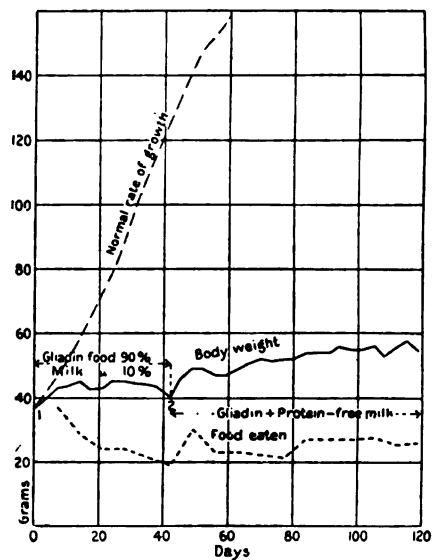
CHART CXI.
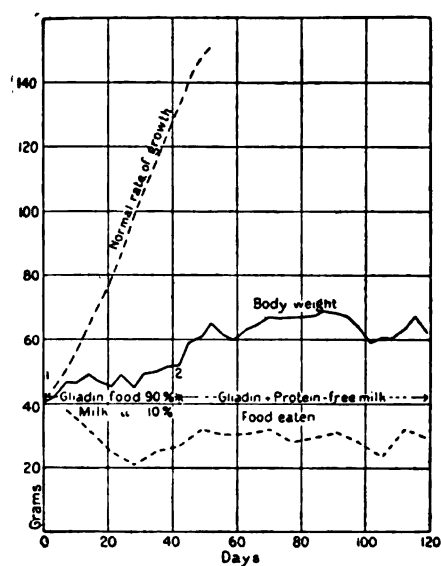
Charts CVIII (rat 214, female), CIX (rat 219, male), CX (rat 220, male), and CXI (rat 213, male) show the failure to induce more than slight growth when gliadin forms the sole protein of the dietary, even under conditions in which most other proteins have been found effective. That the failure to grow is not due to insufficient food intake is evident. The character of the diets is given in the table below.

Period 1:   p. ct.
    Gliadin food: gliadin (from wheat), 18.0; starch, 32.5; sugar,
    17.0; agar, 5.0; salt mixture I, 2.5; lard, 25.0.................   90
    Milk food: Trumilk, 60.0; starch, 15.7; salt mixture I, 1.0; lard,
    23.3...   10

Period 2:   p. ct.
    Gliadin (from wheat).   18.0
    Protein-free milk.....   28.2
    Starch................   20.8
    Agar..................   5.0
    Lard..................   28.0

CHART CXII.

CHART CXIV.
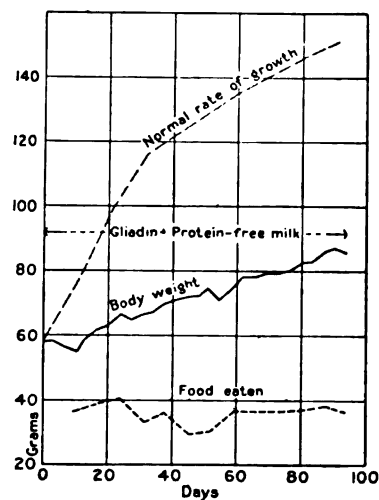
CHART CXIII.
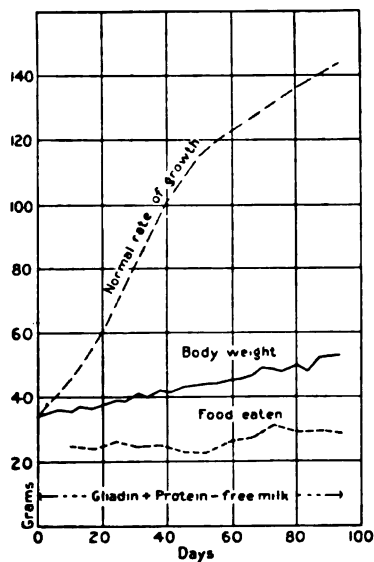
Charts CXII (rat 249, female), CXIII (rat 240, female), and CXIV (rat 254, female) show the failure of the animals to grow normally on a diet containing protein-free milk and gliadin as the sole protein. It will be noted that these animals ate well and that the maintenance was better than with similar gliadin mixtures which contained no protein-free milk. The composition of the food was as follows:

	p. ct.
Gliadin (from wheat)	18.0
Protein-free milk	28.2
Starch	20.8
Agar	5.0
Lard	28.0

CHART CXV.
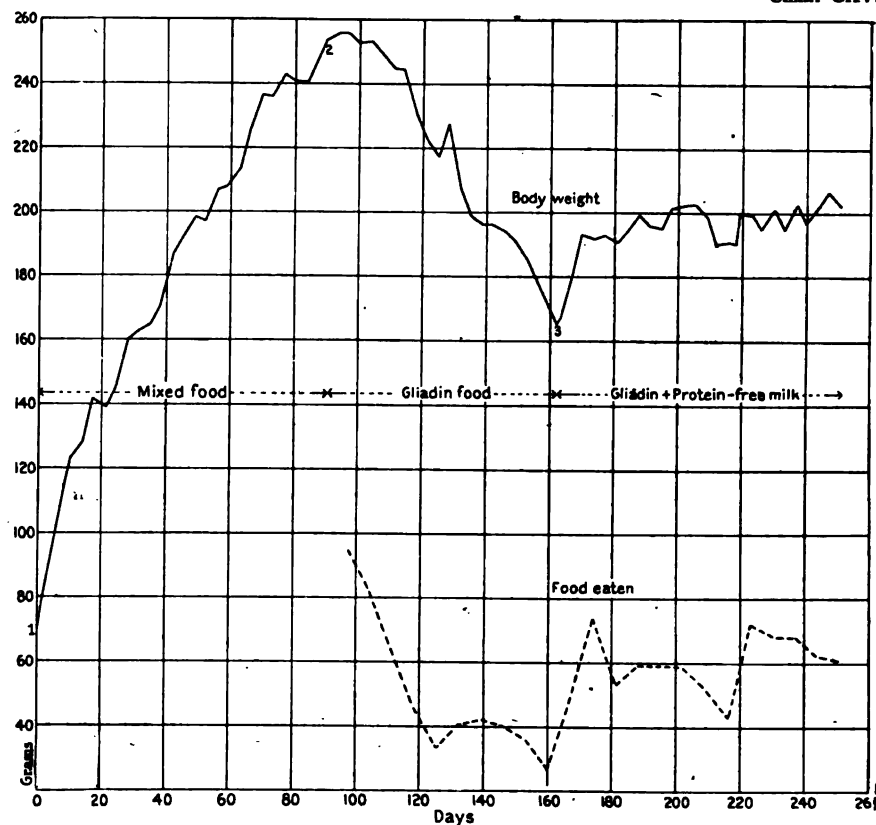
Charts CXV (rat 144, male) and CXVI (rat 134, female) show the failure of animals previously well nourished on a mixed diet (period 1), to be maintained on a diet in which gliadin formed the sole protein (period 2), until protein-free milk was added to the food (period 3). The food during period 1 was mixed. During periods 2 and 3 it was as shown herewith.

Constituents.	Per. 2.		Per. 3.
	p. ct.		*p. ct.*
Gliadin (from wheat)...	18.0	......	18.0
Protein-free milk.......	0.0	......	28.2
Starch...................	29.5 to 34.5		20.8
Sugar...................	15.0	17.0	0.0
Agar...................	5.0	......	5.0
Salt mixture I..........	2.5	......,	....
Lard...................	25.0	30.0	28.0

Chart CXVII (rat 129, female) shows the maintenance in period 2 on a diet containing protein-free milk and gliadin as the sole protein. Note that the animal did not decline like those fed on gliadin without protein-free milk. The preliminary period 1 on a mixed diet, during which the animal was twice pregnant, is introduced to show the excellent previous nutritive condition of the rat. The composition of the food for period 1 was mixed; for period 2 it was as shown herewith.

	p. ct.
Gliadin (from wheat)...	18.0
Protein-free milk.......	28.2
Starch.................	20.8
Agar...................	5.0
Lard...................	28.0

CHART CXVI.
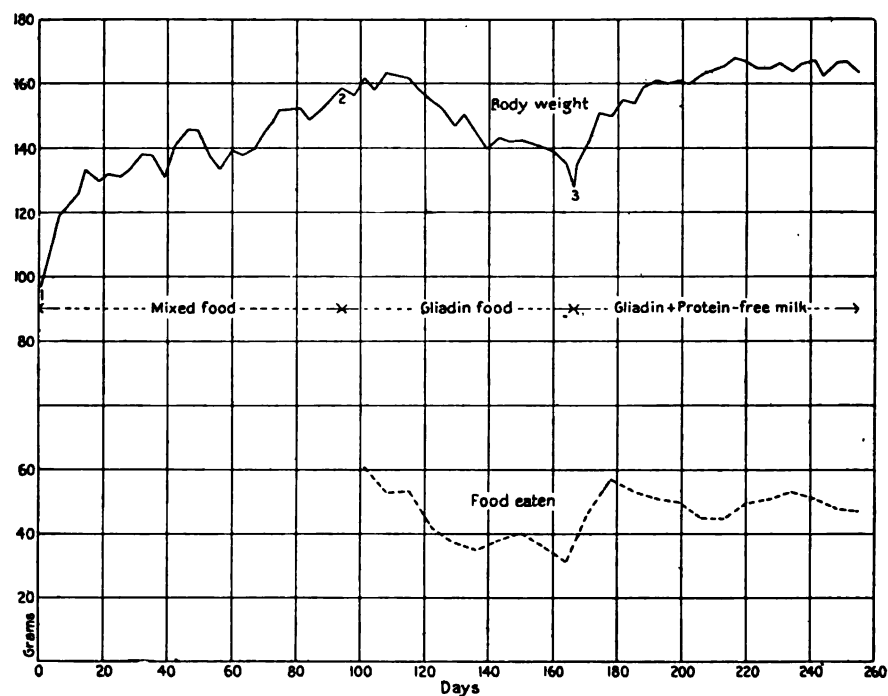
CHART CXVII.
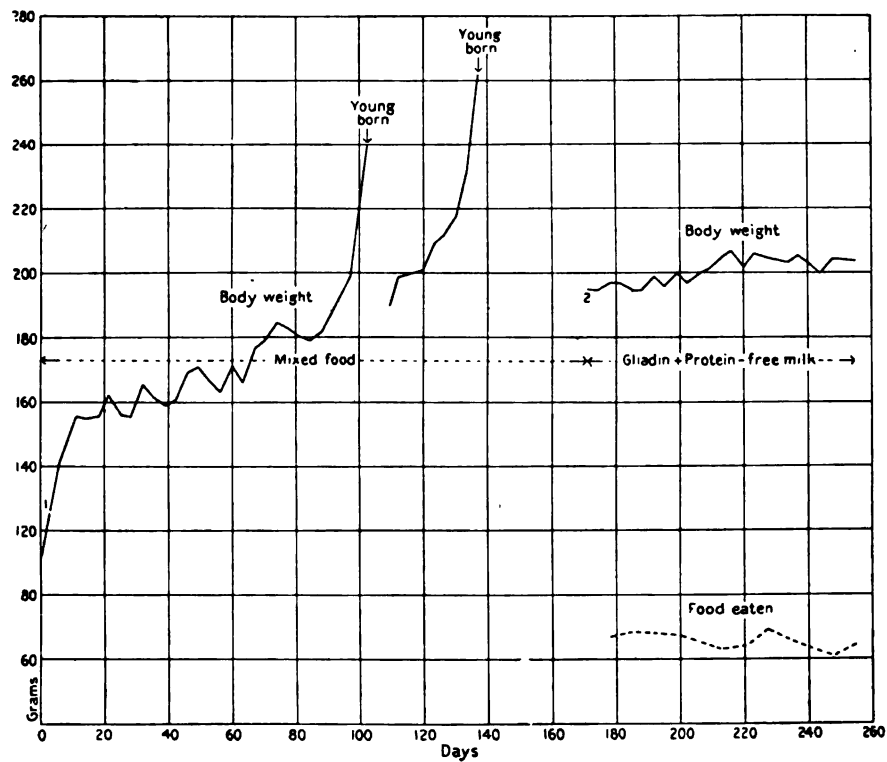
CHART CXVIII.
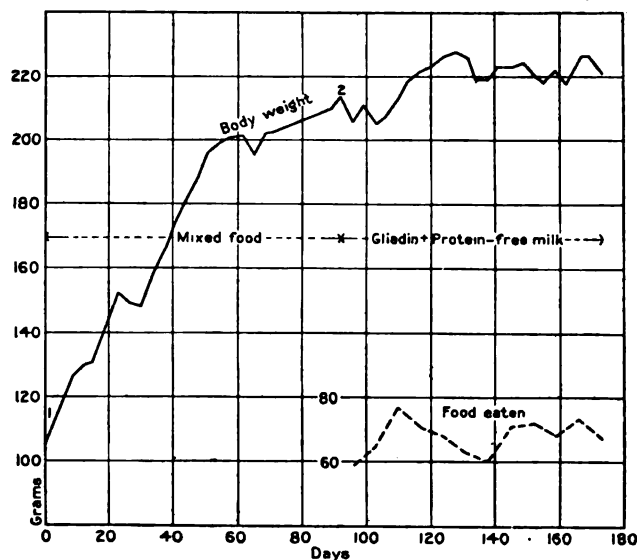
CHART CXIX.
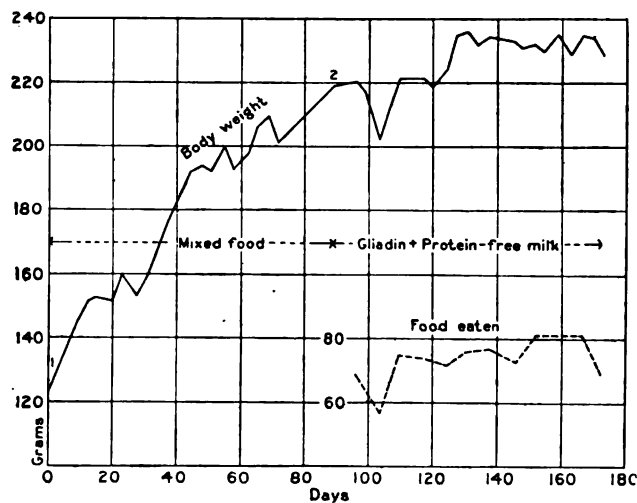
Charts CXVIII (rat 167, male) and CXIX (rat 168, male) show maintenance in period 2 on a diet containing protein-free milk and gliadin as the sole protein. The animals did not decline like those fed on gliadin without protein-free milk. Note their abundant food intake. The preliminary period is introduced to show the excellent previous nutritive condition of the rats. The composition of the food was mixed during period 1; for period 2 it was as shown herewith.

	p. ct.
Gliadin (from wheat)...	18.0
Protein-free milk.......	28.2
Starch.................	20.8
Agar...................	5.0
Lard..................	28.0
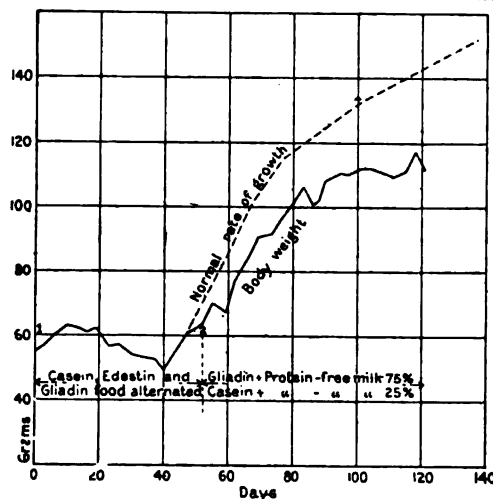
CHART CXX. CHART CXXI.
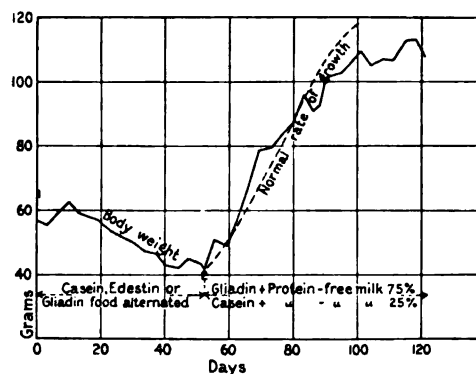
Charts CXX (rat 208, female) and CXXI (rat 206, female) show, in period 1, failure to grow on the diet indicated below; and, in period 2, nearly normal growth on a diet containing protein-free milk in which one-quarter of the gliadin, previously found inadequate to induce growth, was replaced by casein. Note the small quantity of casein which suffices to promote growth instead of standstill. This emphasizes the different nutritive value of casein and gliadin. The diets consisted of—

Constituents.	Per. 1.	Constituents.	Per. 2.
	p. ct.		*p. ct.*
Casein or }		Gliadin food (gliadin (from wheat), 18.0;	
Edestin or }...	18.0	protein-free milk, 28.2; starch, 20.8;	
Gliadin }		agar, 5.0; lard, 28.0).................	75
Starch..........	32.5	Casein food (casein, 18.0; protein-free	
Sugar...........	17.0	milk, 28.2; starch, 23.8; agar, 5.0;	
Agar............	5.0	lard, 25.0)............................	
Salt mixture I...	2.5		25
Lard............	25.0		

CHART CXXII.

Chart CXXII (rat 179, female). Period 1 shows maintenance without growth on a diet containing salt mixture I (no protein-free milk) and casein as the sole protein. This should be contrasted with numerous similar experiments in which the inorganic constituents of the diet were present in the

form of protein-free milk. Period 2 shows the influence of the substitution by casein of one-fourth of the gliadin in a dietary repeatedly shown to suffice for maintenance but not for growth. This emphasizes the different nutritive value of casein and gliadin. The composition of the diets was as shown below.

Constituents.	Per. 1.	Constituents.	Per. 2.
	p. ct.		*p. ct.*
Casein...........	18.0	Gliadin food (gliadin (from wheat),	
Starch...........	32.5	18.0; protein-free milk, 28.2;	
Sugar...........	17.0 to 20.0	starch, 20.8; agar, 5.0; lard, 28.0).	75
Agar...........	5.0	Casein food (casein, 18.0; protein-	
Salt mixture I...	2.5	free milk, 28.2; starch, 23.8;	
Lard...........	22.0 to 25.0	agar, 5.0; lard, 25.0).............	25
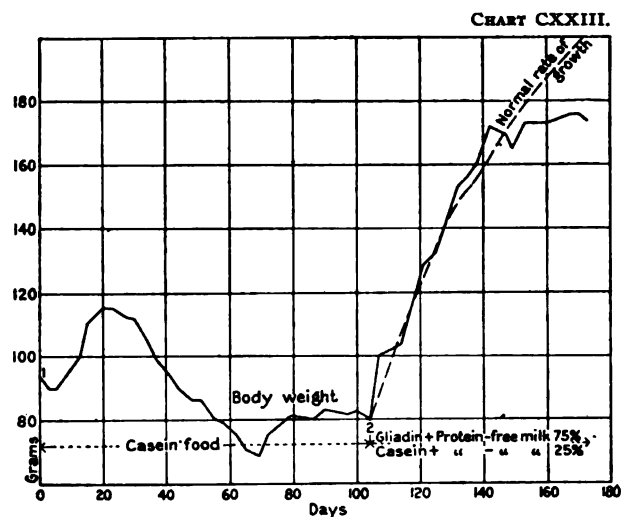
CHART CXXIII.

Chart CXXIII (rat 173, male). Period 1 shows imperfect maintenance without growth on a diet containing salt mixture I (no protein-free milk) and casein as the sole protein. This should be contrasted with numerous similar experiments in which the inorganic constituents of the diet were present in the form of protein-free milk. Period 2 shows the influence of the substitution by casein of one-fourth of the gliadin in a dietary repeatedly shown to suffice for maintenance but not for growth. This emphasizes the different nutritive value of casein and gliadin. The composition of the diets was—

Constituents.	Per. 1.	Constituents.	Per. 2.
	p. ct.		*p. ct.*
Casein...........	18.0	Gliadin food (gliadin (from wheat),	
Starch...........	32.5	18.0; protein-free milk, 28.2;	
Sugar...........	17.0 to 20.0	starch, 20.8; agar, 5.0; lard, 28.0).	75
Agar...........	5.0	Casein food (casein, 18.0; protein-	
Salt mixture I....	2.5	free milk, 28.2; starch, 23.8; agar,	
Lard...........	22.0 25.0	5.0; lard, 25.0)....................	25

CHART CXXIV.
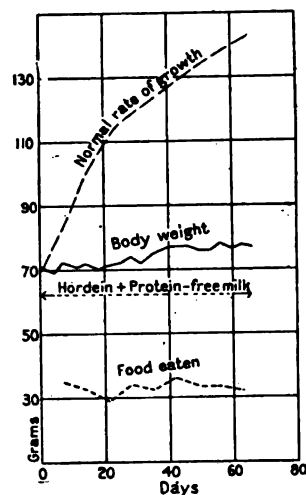
CHART CXXV.
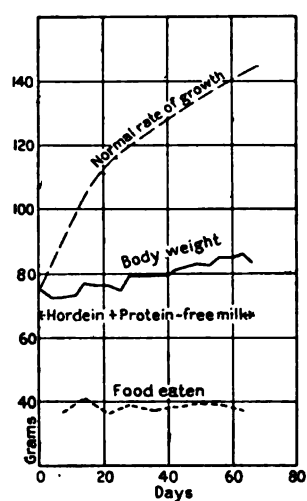
Charts CXXIV (rat 256, female) and CXXV (rat 255, female) show maintenance without growth of medium-sized rats on a diet of protein-free milk and hordein, from barley, as the sole protein. Note the undiminished appetite during course of experiment. Precisely similar mixtures containing other single proteins have sufficed to induce growth. This experiment demonstrates the different nutritive value of hordein and most other proteins and its resemblance in this respect to the chemically similar protein gliadin. This is a marked instance of the relation of the chemical constitution of the protein to nutrition. The composition of the food was as shown herewith.

	p. ct.	
Hordein...............	18.0	....
Protein-free milk....	26.2	....
Starch...............	16.8 to 18.8	
Agar.................	5.0	....
Lard.................	30.0	32.0
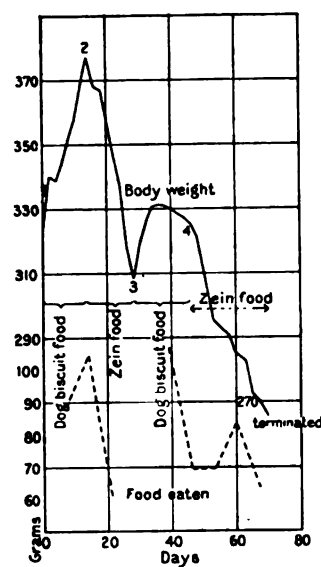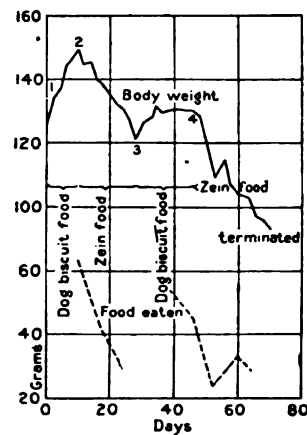
Charts CXXVI (rat XI) and CXXVII (rat XIV) show the failure of well-nourished animals (see period 1) to be maintained on a diet in which zein formed the sole protein. The diet consisted of—

Constituents.	Periods 1 and 3.	Constituents.	Per. 2.	Per. 4.
	p. ct.		p. ct.	p. ct.
Dog biscuit......	58.33	Zein..........	16.89	10.77
Lard...........	41.66	Starch........	10.14	23.70
		Sugar.........	8.78	21.54
		Salt mixture..	3.38	2.15
		Agar..........	10.14	5.17
		Lard..........	50.67	36.63

CHART CXXVIII.
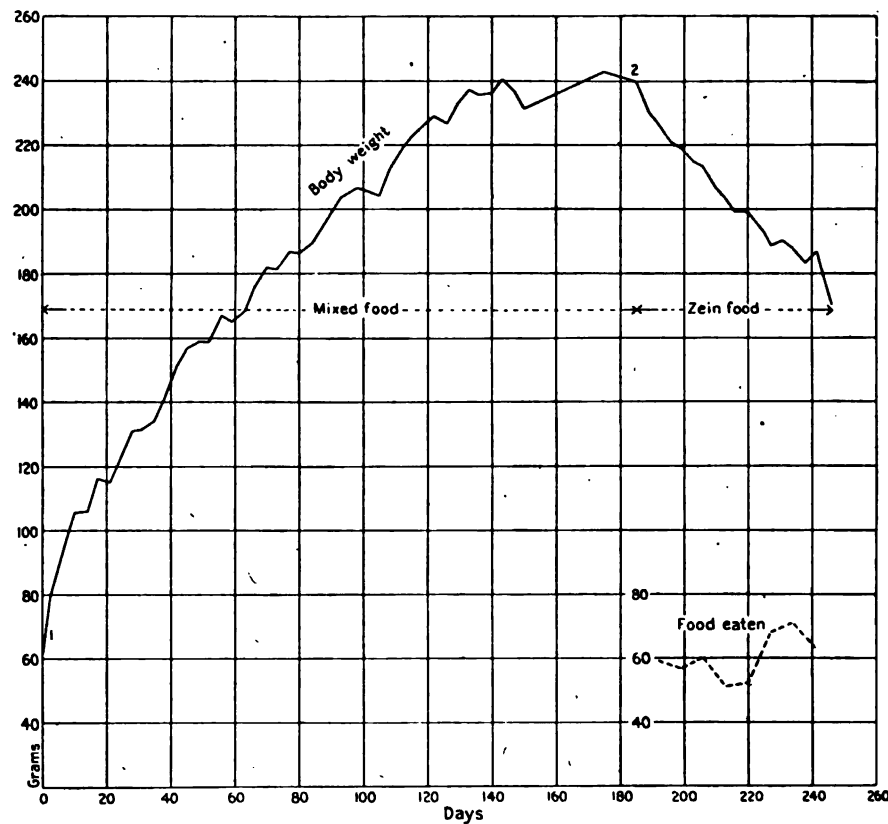
Chart CXXVIII (rat 146, male) shows the failure of a well-nourished rat (see period 1) to be maintained on a diet containing protein-free milk and zein as the sole protein. It should be noted that precisely similar mixtures in which zein was replaced by any of the other proteins studied, sufficed either to induce growth or at least to maintain bodyweight for an equally long period. Attention is directed to the continued fall in weight despite the large food intake. The composition of the food was mixed for period 1; for period 2 it was as shown herewith.

Period 2.

	p. ct.
Zein	18.0
Protein-free milk	28.2
Starch	23.8
Agar	5.0
Lard	25.0

CHART CXXIX.

Chart CXXIX (rat 157, male) shows the failure of a well nourished rat (see period 1), to be maintained on a diet containing protein-free milk and zein as the sole protein. It should be noted that precisely similar mixtures in which zein was replaced by any of the other proteins studied, sufficed either to induce growth or at least to maintain body-weight for an equally long period. Attention is directed to the continued fall in weight despite the large food intake. The composition of the food was mixed for period 1; for period 2 it was as shown herewith.

Period 2.	p. ct.
Zein	18.0
Protein-free milk.	28.2
Starch	23.8
Agar	5.0
Lard	25.0

NEW HAVEN, CONNECTICUT, U. S. A.,
    JULY 1, 1911.

HIGH TEMPERATURE
GAS THERMOMETRY

BY

ARTHUR L. DAY AND ROBERT B. SOSMAN

WITH

AN INVESTIGATION OF THE METALS

BY E. T. ALLEN

CARNEGIE INSTITUTION OF WASHINGTON

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INTRODUCTION.

The year 1900 marked the close of an investigation of the gas thermometer at high temperatures which had been prosecuted with great vigor at the Reichsanstalt for nearly ten years. The temperature scale had not been extended beyond 1150° C., the stopping-place of most of the earlier investigations, but a scale had been established in which there was a strong feeling of confidence, and which is to-day in general use. The absolute accuracy was believed to be about 1° at 400° and 2° to 3° at 1150°. Temperatures higher than this were extrapolated by thermo-electric or radiation methods, at first with confidence, afterward with some misgiving, concerning which a good deal is said in the pages which follow. This scale and extrapolation scheme have never been formally adopted by international agreement, although no doubt such an agreement would have been of considerable value. In the absence of prescribed procedure the details of the extrapolation have differed considerably in the hands of different experimenters, which has caused an uncertainty in the interpretation of the higher temperatures, amounting to 50° at the platinum point. It was primarily for the purpose of clearing up this uncertainty in the region above 1150° and providing a sound basis of temperatures for the mineral work of this laboratory that this problem was taken up again.

The present investigation was begun in 1904 under the auspices of the U. S. Geological Survey and on the fourth floor of its building in the busiest portion of Washington. Here the conditions of light, constant temperature, and stability were very ill-adapted for quantitative work of the high order of accuracy to which it was desired to attain. It was therefore most fortunate for the success of this and other quantitative work which had hitherto been carried on with considerable difficulty, when the Carnegie Institution of Washington provided a new and well-equipped laboratory for it in 1907. The preliminary experimental work and all the measurements of the first series here described (to 1150°) were made in the Geological Survey; those of the second series, including all the observations of temperatures above 1150°, were made in the Geophysical Laboratory. The facilities provided in the new laboratory permitted measurements of great refinement.

Dr. J. K. Clement, who shared the burden of observations under the unfavorable conditions of the Survey building, withdrew in the spring of 1907 to become physicist of the Technologic Branch of the Survey (now the Bureau of Mines). The determination of the expansion coefficient of the platin-iridium bulb (p. 27), and all the work with the platin-rhodium bulb (p. 48 et seq.) was done by Day and Sosman.

If it is permitted to a student who has been actively at work upon this problem of high temperature measurement, partly in the Reichsanstalt and partly independently, for a nearly continuous period of fourteen years, to indulge in speculation of a somewhat irresponsible kind, this may be said apropos of the present status of absolute measurements of high temperature: The gas thermometer with a bulb of platin-rhodium is thoroughly trust-

worthy and free from the large and more or less indeterminate errors char-
acteristic of much of the earlier work, but the upper limit of temperature
attainable with this bulb is nearly, if not quite, reached at 1550°. The
platin-rhodium alloy is not rigid enough to be depended upon for constant-
volume measurements at higher temperatures. The iridium bulb in use at
the Reichsanstalt has the required stiffness, but can not be used for the
calibration of thermo-elements at temperatures above 1550° without con-
taminating them beyond the possibility of restoration for accurate work.
It may prove practicable to coat the surface of the bulb or the exposed
wire with a viscous silicate or oxide which will prevent the sublimation of
iridium, but all the efforts thus far made to find such a substance have been
without success. And even if this proved successful it is unlikely that it
would add more than 100 or 200 degrees to the existing scale.

A better plan might be to abandon platinum metals altogether in the
near neighborhood of their melting temperature and to substitute tungsten
or tantalum in a bath of stable oxides or silicates of sufficient fluidity to
permit it to be stirred. Such a bath could perhaps be heated by passing
the current directly through it, as in the barium chloride bath introduced
by the General Electric Company a few years ago. Water-jacketing would
protect the containing vessel, and a stirring mechanism and diminished
pressure above the surface of the liquid, with a bulb of appropriate shape,
would make it entirely practicable to maintain a nearly constant pressure
inside and outside of the bulb. The bath would protect the bulb from oxida-
tion and the stirring would provide a constant temperature about it—which
is the greatest uncertainty in the present system of gas-thermometer meas-
urement. All depends upon discovering a bath which will meet these
difficult conditions. In a field which is still quite unexplored perhaps we
need not altogether despair of finding it.

Meanwhile accurate gas thermometry up to 1550° insures the accurate
calibration of optical and radiation pyrometers, which are well founded
theoretically, convenient to use, and without an upper temperature limit.
There is no need that the measuring instrument be in contact with the hot
body whose temperature is desired, nor is it always necessary that any
portion of the apparatus be heated to this temperature. The sensitiveness
of most of these instruments is relatively low, but at extreme temperatures
it is quite sufficient for industrial and probably for scientific uses also for
many years to come. It would therefore appear that we are now well served
in the matter of accurate and trustworthy high-temperature standards and
convenient measuring devices, and if the need for a more extended and
accurate scale shall arise it is by no means certain that the limit of standard
temperature definition by means of the gas scale has been reached at 1550°.

HIGH TEMPERATURE GAS THERMOMETRY.

I. TEMPERATURE DEFINITION.

The measurement of temperature differs from most fundamental physical measurements in that the temperature function is not additive. There is no temperature unit corresponding to a foot-rule or meter-stick which can be applied successively to measure a high temperature as we would measure the height of a room. Two temperatures of one degree can not be combined in any way to give a temperature of two degrees. Temperature measurement is therefore wholly a matter of arbitrary definition, of selecting some convenient phenomenon (like the expansion of a gas) which varies continuously and as nearly as possible uniformly with temperature changes, of providing convenient arbitrary units of subdivision, and then of observing the expansion of the gas, or other phenomenon, under the conditions which surround the unknown body whose temperature is desired. The expansion of hydrogen has been established by international agreement as our fundamental measure of temperature. The gas thermometer is therefore now the standard thermometer in terms of which all temperatures are defined.

The theoretical interest in gas thermometry centers about the quantitative relation existing between the increase in the temperature of the gas expanding under constant pressure or volume and the quantity of heat required to produce it. It is a somewhat inaccessible question by reason of the difficulty of approaching it experimentally with the required accuracy. Although the amount of the expansion of gases is more closely proportional to the quantity of heat applied than that of liquids or solids, no strictly "perfect gas" in this sense has been found. The amount of the divergence between the expansion and the quantity of heat which produces it is slightly different with different gases, and is also slightly different for the same gas at different temperatures. In the case of nitrogen, which has a greater range of practical utility than other gases thus far studied, the expansion curve diverges slowly from the regular curve of a perfect gas as the temperature increases, but the amount of its departure does not attain the magnitude of one degree centigrade until the temperature reaches 1100° or more, and the magnitude of this correction factor, if it is to be regarded as a correction factor, is probably of the same order as the observation errors of an actual gas thermometer in the present stage of its development. For this reason, these theoretical considerations, which have been admirably treated by Buckingham in a paper, "On the establishment of the thermodynamic scale of temperature by means of the constant-pressure thermometer" (Bull. Bur. Standards 3, 237, 1907), do not seriously affect the definition of an accurate and practicable high-temperature scale by means of the gas laws.

Buckingham defines the gas scales very clearly in this way:

"Two principal methods of gas thermometry are in use. In the constant-volume thermometer a mass of gas is kept at constant volume and its pressure observed at the melting-point of ice, at the condensing-point of steam (under standard atmospheric pressure), and at the temperature to be determined. If these three pressures be denoted by p_0, p_{100}, and p, the centigrade temperature according to the scale of this thermometer is by definition,

$$t_v = 100 \frac{p - p_0}{p_{100} - p_0}$$

The numerical value thus assigned to a given temperature depends slightly on the initial pressure and is somewhat different for different gases. * * *

"In the constant-pressure thermometer a mass of gas is kept at constant pressure, and its volume observed at the two standard temperatures and at the temperature to which a numerical value is to be assigned. If these volumes be v_0, v_{100}, and v, the centigrade temperature according to the scale of this thermometer is by definition

$$t_p = 100 \frac{v - v_0}{v_{100} - v_0}$$

The resulting value depends somewhat on the magnitude of the constant pressure and on the nature of the gas used."

Lord Kelvin has proposed, and the physicists who choose to consider the problem from the theoretical side (including Buckingham) have generally approved the proposal, to go further and interpret all temperatures strictly in terms of a hypothetical "perfect gas," in which the expansion (which defines the temperature), whether under constant volume or pressure, would increase exactly in proportion to the quantity of heat required to produce it. This would have the obvious advantage that temperature definition would become uniform and independent of the properties of any particular substance, but its adoption will be of little actual service to high-temperature thermometry until experimental measurements of greater scope and precision are available.

The direct experimental measurement of the degree of departure of an actual gas from this ideal state (the Joule-Thomson porous-plug experiment) involves the determination of two extremely small magnitudes which have not (as yet) been measured separately at all, nor together except with the greatest difficulty. From such results as we have it appears, as has been stated, that the difference between the expansion of the thermodynamically perfect gas and the actual expansion, from the low initial pressures usually used, of any of the gases hitherto employed for the purpose (H_2, N_2, CO, CO_2, O_2) approaches $1°$ at $1100°$. Even for work of the highest precision, the constant-pressure or the constant-volume gas scale is therefore quite as serviceable as the thermodynamic scale, at the present stage of development of the subject.

By international agreement and nearly universal practice, two fixed temperatures are accepted as the basis of the modern temperature scale: The melting-point of pure ice and the boiling-point of pure water, both at normal atmospheric pressure (equal to 760 mm. of mercury). The interval included

between these two temperatures is subdivided into 100 parts by measuring the constant volume expansion of hydrogen from an initial pressure of 1 m. of mercury throughout this interval.

The actual determination of these intervals or degrees centigrade was made by Chappuis at the Bureau Internationale des Poids et Mesures at Paris in 1888, and is a work of such painstaking character in most particulars that no investigator has found it necessary to repeat it since that time. The probable accuracy of the individual degrees thus determined, that is, of the international scale of temperatures between 0° and 100°, is stated by Chappuis to be 0.002.[1]

To extend the scale beyond these limits in either direction, it is (theoretically) only necessary to continue the measurement of the expansion of hydrogen under the same conditions down to or up to any desired temperature. In practice, this procedure encounters various experimental difficulties which increase rather rapidly as we go farther away from the temperatures of every-day life.

These experimental difficulties serve to place definite limits upon the accuracy of temperature measurement at present attainable in different parts of the field, of which it is important to obtain a clear idea in order to be able to form a sound judgment of the probable significance of measurements at widely different temperatures. If we are told, for example, that a solution boils at 90.27°, we recognize that this accuracy is entirely practicable. If, on the other hand, platinum is said to melt at 1755.46°, it is of advantage to know that the last two figures are wholly without significance, and the fourth is uncertain.

There is no denying the fact that a great deal still remains to be done upon the experimental side before the steadily advancing requirements of both science and industry in the matter of a trustworthy temperature scale, of sufficient accuracy and more particularly of sufficient range, can be satisfied. It is no disparagement of the present system of temperature definition to say that the gas thermometer itself is a complicated and cumbersome instrument to use in any of the forms which have hitherto been devised, and possesses limitations, both of range and accuracy, which are difficult to overcome.

One consequence of this, particularly in the region of high-temperature measurements, is that temperatures easily come to be regarded with unwarranted confidence in the hands of those who have never acquired a first-hand knowledge of these limiting conditions. This confidence has no doubt been fostered by the comparative ease with which *relative* measurements of temperature can be made, even in the more inaccessible parts of the scale, with the thermo-element and the resistance thermometer. These devices are sensitive to temperature differences of the order of magnitude of 0.01° throughout their entire range, but they are dependent absolutely upon fundamental measurements with the gas thermometer for their evaluation in terms of the generally accepted degree centigrade.

[1] In a recent paper, "Some new measurements with the gas thermometer" (Amer. Jour. Sci. (4), 26, 405-463, 1908), the authors gave it as their opinion that the determination of the expansion coefficient of the thermometer bulb used by Chappuis, which is of course an important factor in the experimental problem, would not warrant an assumption of accuracy greater than 0.005°. To this Chappuis replied in a personal letter (1909) that considering all the factors of the problem, and subsequent experience, he still thought 0.002° a fair estimate of the probable error of the scale in the region between 0° and 100°.

It is sufficiently obvious, though often carelessly overlooked, that no method of temperature measurement, however sensitive or adaptable it may be, can yield temperatures of greater absolute accuracy than the system in terms of which those temperatures are defined. With the gas thermometer as our basis of definition, therefore, we shall know our temperatures with just the certainty which it is able to furnish and no more. There is, to be sure, some justification for expressing the results of thermo-electric or resistance measurements in units smaller than the errors of the fundamental scale, where only comparative measurement is involved; but such measurements must not be used without regard to this limitation.

It is not the purpose of the present paper to discuss the general problem of thermometry, or the particular advantages of one system of thermometric measurement over another in laboratory or industrial practice, but merely to describe the work which has been done in recent years to increase the range and accuracy of the temperature scale, upon which the various devices for measuring high temperatures depend for their calibration. Neither is it necessary to include any discussion of the relative theoretical merit or experimental practicability of the constant-volume and constant-pressure methods of gas thermometry. The reader will find it in Buckingham's paper already mentioned, in Barus's review[1] of the progress of pyrometry for the Paris Congress in 1900, as well as in earlier discussions to which they have referred. The choice of the one or the other method is likely to be governed by the taste or predilection rather than by the necessities of the individual experimenter. Neither system possesses decided advantages over the other. Most of the recent measurements have been made with the constant-volume system.

2. HISTORICAL.

To reach a satisfactory estimate of the degree of confidence to be accorded to the new absolute measurements of high temperature requires some historical perspective, for the development of the experimental problem has now been going on for nearly a century. It will therefore be well to review somewhat briefly the chief steps in its progress for two explicit reasons: (1) In order that we may form a sound and properly critical judgment of the trustworthiness of the results so far attained; and (2) that future investigators may be enabled to avoid the limitations which have arisen in the earlier work.

We will therefore attempt to follow the development of the gas thermometer through some of the vicissitudes of its long service as a standard high-temperature measuring instrument. For it was understood from the beginning that the gas thermometer, with its cumbersome bulb and equipment, must always remain an instrument of reference rather than of practical utility.

Prinsep, 1828.—The first pyrometer based on the expansion of gases, so far as we now know, was made by Prinsep[2] and described by him in 1828. He used a bulb of gold, connected with a sensitive manometer with

[1] Carl Barus, "Les progrès de la pyrométrie," Rapports présentés au Congrès Internationale de Physique, 1900, vol. I, pp. 148-177.
[2] Phil. Trans., 1828, 79-95; Ann. d. chim. et d. phys. (2), 41, p. 247, 1829.

which to maintain the gas (air) at constant pressure within, and connected also with a reservoir of olive oil; the expansion of the air in the bulb displaced a proportionate amount of oil, which was caught and weighed and the temperature calculated. With this apparatus Prinsep made excellent temperature measurements, chiefly of the melting-points of the alloys of gold, silver, and platinum, which bear his name and are still sometimes used. The usefulness of Prinsep's thermometer was limited by the comparatively low melting temperature of the gold bulb.

Pouillet, 1836.—Prinsep was quickly followed by Sir Humphrey Davy and several others, all employing the expansion of air at constant pressure, but none contributing materially to the improvement of Prinsep's apparatus until Pouillet[1] constructed his instrument in 1836. Pouillet's bulb was of platinum, which enabled him to reach the highest temperatures, and his experimental procedure, with but slight modifications, is that employed to-day by Callendar and his associates, who have always expressed a preference for the constant-pressure method. It was Pouillet also who made and calibrated the first practicable thermo-element (platinum-iron), who anticipated the method of measuring temperature through determinations of the specific heat of platinum subsequently developed by Violle, and who made some study of the radiant energy sent out by glowing solids. In varying degree and with many of the inevitable limitations of the pioneer, Pouillet not only established gas thermometry upon a sound basis, but introduced several of the important practical methods of pyrometry (specific heat, thermo-electricity, radiation) which have been in use since his time.

Following Pouillet, therefore, the advancement of pyrometric measurement became to a considerable degree a question of perfection of experimental detail rather than of the development of new principles, and so, with one or two exceptions which will be noted presently, it has since remained. Regnault in particular made a number of improvements in the Pouillet instrument in 1847.[2]

The first gas thermometer which measured the expansion of the gas under constant volume appears to have been built by Silbermann and Jacquelin in 1853, but it was only indifferently successful. Effective use was first made of the method in the work of Becquerel described below.

St. Claire-Deville and Troost,[3] 1857.—It was soon after this that a real catastrophe occurred in the development of the gas thermometer. Deville and Troost (1857), desiring to use a heavier gas in place of air, introduced iodine into a bulb of porcelain and made determinations of a number of constant temperatures, most conspicuous among which, in the discussion which followed, was the boiling-point of zinc, which they ascertained to be 1040°.

Edmond Becquerel,[4] 1863.—Becquerel followed in 1863, using the Pouillet apparatus with platinum bulb and air as the expanding gas, and reached the conclusion that zinc boiled at 932°, more than 100° lower. In the controversy which followed, and which was maintained from both sides with considerable bitterness, these observations were repeated by both observers

[1]Compt. rend., **3**, 782–790, 1836.
[2]Relation des Expériences, Mem. Acad. Sci., Paris, **21**, p. 168, 1847.
[3]Deville and Troost; Compt. rend. **45**, 821–825, 1857; **49**, 239–242, 1859; Ann. d. chim. et d. phys. (3), **58**, 257–299, 1860.
[4]Ann. d. chim. et d. phys. (3), **68**, 49–143, 1863.

with substantial confirmation of the first results, Deville and Troost maintaining from experiments of their own that Becquerel's platinum bulb was permeable to hot gases and that his results must of necessity be too low. To this contention Becquerel replied convincingly by using a porcelain bulb himself (still retaining air as the expanding gas), with both the constant-volume and constant-pressure methods of measurement, and announced a result (891°) even lower than his previous determination. Notwithstanding this, Deville and Troost were unwilling to regard the result as conclusive, and looked upon the discrepancy between Becquerel's earlier and later results (932° and 891°) with unconcealed suspicion. They reiterated their belief that the platinum bulb was permeable and that Becquerel's results with porcelain bulbs were still too low through failure to expose the bulb directly to the zinc vapor. Becquerel's bulb had been shielded from the direct action of the zinc by a protecting tube. Deville and Troost then repeated their own measurements and confirmed their earlier result. Becquerel, following, insisted that his measurements with the platinum bulb were not seriously affected by permeability to hot gases, a property with which he appeared to be familiar, and explicitly criticized the use of iodine by Deville and Troost.

The discussion ended here for the moment, without a decisive issue, but subsequent experience has substantially confirmed Becquerel in his contention and his numerical results. The high value obtained by Deville and Troost was undoubtedly due chiefly to the dissociation of the iodine at high temperatures, but this was not discovered until afterward in 1879 by Victor Meyer.[1]

The real catastrophe in the development of the gas thermometer, however, does not lie in the uncertainty of the results obtained with it by these distinguished observers, nor yet in the subsequent discovery that iodine is an inappropriate expanding medium with which to measure temperature; but rather in the discredit in which the platinum bulb came to be held and the universal substitution therefor of porcelain—a material of wholly uncertain chemical composition and physical characteristics. This was a backward step which was not retrieved for more than thirty years.

Deville and Troost[2] then entered upon a long series of experiments with porcelain glazed inside and outside with feldspar, in the course of which it appeared that the expansion of the bulb, a factor of great importance both then and now in gas thermometry, was variable with the temperatures to which it had previously been exposed. These irregularities diminished with continued use and were thought to become negligible in bulbs of Bayeux porcelain after a few heatings to a very high temperature.

Regnault.[3] *1861.*—During the period of this investigation Regnault was at work upon a displacement method (boiling mercury in an iron flask and estimating the temperature from the quantity remaining in the flask after cooling), which did not prove satisfactory. Schinz, Berthelot, and Weinhold suggested some modifications of this and other contemporary methods, but none of them proved of permanent value.

[1] V. and C. Meyer, Ber. Deutsch. Chem. Ges., 12, 1426-1431, 1879. V. Meyer, ibid., 13, 394-399, 1010-1011, 1880.
[2] Compt. rend. 57, 897-902, 1863; 59, 162-170, 1864.
[3] Ann d. chim. et d. phys. (3), 63, 39-56, 1861.

Erhard and Schertel,[1] 1879.—Erhard and Schertel redetermined the melting temperatures of the Prinsep alloys in 1879, using a bulb of Meissen porcelain and air as expanding gas with considerable success. Their work contributed little of novelty, but was carefully done and the results have since been extensively used.

In 1880 Deville and Troost reappeared in the field, after a long silence, and also proposed a displacement scheme containing some improvements over the apparatus proposed by Regnault. Nitrogen was here used in place of air, but otherwise the method possessed insufficient accuracy to secure for it general approval. In the same year they published a summary of all their work on boiling zinc, giving 942° as the mean of 27 determinations, which was (for that time) in good agreement with Becquerel's first value, 932°.

Violle,[2] 1882.—In the same year (1882) Violle, using Deville and Troost's methods and apparatus, found zinc to boil at 930° and thus added a further degree of probability to the determination of Becquerel. Violle continued his researches by determining with the gas thermometer the specific heat of platinum for a number of temperatures up to 1200°, and then extrapolating with this constant for the measurement of temperatures beyond the reach of the thermometer itself. He thus determined the melting-point of gold (1045°), of palladium (1500°), and of platinum (1775°), constants which continued in general use as standard temperatures for some years.

In the decade between 1882 and 1892 contributions to gas thermometry and the measurement of high temperatures are few and unimportant, but work was begun in those years on both sides of the Atlantic which, for the experimental skill and persistence with which the experimental difficulties and limitations were pursued and successively overcome, surpasses any effort which has been made either before or since that time. These were the investigations of Barus at the U. S. Geological Survey in Washington and of Holborn and his colleagues at the Reichsanstalt in Charlottenburg.

Barus[3] (1889) recognized, as no observer who preceded him had done, the superlative importance of a uniform temperature distribution about the gas thermometer bulb for purposes of high-temperature measurement, and he took the most extraordinary precautions to maintain it. A temperature of 1000° C. or more is not attained without very steep temperature gradients in the region immediately surrounding the zone of highest temperature. It is therefore a problem of great difficulty to introduce a bulb of from 10 to 20 cm. in its largest dimension into this hot zone without leaving some portion of it projecting out into a region 200° or 300° lower in temperature. Burning mixtures of gas and air for heating purposes also contributed to the irregularity and uncertainity of the temperature distribution about the bulb. Barus sought to avoid this by a method of great ingenuity, but also of great technical difficulty. He inclosed his bulb within a rapidly revolving muffle which by its motion protected every portion of the bulb from direct exposure to a particularly hot or a particularly cold portion of the adjacent furnace. This complicated furnace structure and consequently inaccessible

[1] Jahrb. f. Berg-u. Hüttenwesen (i. Sachsen), 1879. p. 154.
[2] Compt. rend., 94, 720-722, 1882.
[3] Bull. 54, U. S. Geol. Survey, 1889. Die Physikalische Behandlung und die Messung hoher Temperaturen. Leipzig, 1892.

position of the bulb made it impossible to introduce into the region about the bulb the substances whose temperature constants were to be measured and compelled him to use thermo-elements which were first calibrated by exposure in the furnace with the bulb and then used independently to measure other desired temperatures. The thermo-element has continued in general use in this intermediary rôle since that time.

Barus and the Thermo-element.—In the preparation and use of thermo-elements Barus also made much more extensive and elaborate studies than any one who has followed him. He first investigated a great number of substances, both pure metals and alloys, and measured and tabulated their electro-motive forces for different absolute temperatures. From these an element made from pure platinum and an alloy containing 90 parts platinum and 10 parts of iridium was finally selected for his standard work. The wires of this thermo-element were passed through the axis of the revolving muffle and into a re-entrant tube in the bulb of the gas thermometer, where the hot junction was brought to lie in the geometrical center of the spherical porcelain bulb. Here its electromotive force was read for a considerable number of measured temperatures and its curve determined. If the wires became contaminated by exposure to furnace gases they were melted and redrawn. This plan was pursued most conscientiously and a considerable number of temperature constants from the melting-point of zinc (424°) to the melting-point of gold (1093°) and of copper (1097°) determined.

It is an unfortunate accident that history has failed to record Barus's name along with that of Le Chatelier[1] in the development of the thermo-element for purposes of high-temperature measurement. It hardly admits of question that Barus contributed incomparably more to our knowledge of the thermo-electric properties of the different metals and their use than his distinguished French contemporary, but the 10 per cent iridium alloy which he finally selected proved to be less serviceable than the 10 per cent rhodium alloy developed by Le Chatelier, probably by reason of the greater volatility of the iridium and a consequent slow change in its readings. And so we find the Le Chatelier platin-rhodium thermo-element in use to-day the world over, while the magnificent pioneer work of Barus remains but little known.

Holborn and Wien, 1892.—In the same year in which Barus published his final memoir on the gas thermometer and the thermo-element (1892) Holborn and Wien published a paper, "Ueber die Messung hoher Temperaturen,"[2] covering nearly the same ground in the same general way, but with somewhat different results. Both used air as the expanding gas, both used thermo-elements to transfer the standard gas temperatures over to the substance to be measured; but Holborn and Wien attained to higher temperatures (above 1300°), while Barus took much greater precaution than his German contemporaries to secure a uniform temperature about his bulb. The arrangement adopted by Holborn and Wien possessed the further advantage that the thermo-element was entirely inclosed within the bulb itself and so was well protected against the contaminating influence of furnace gases besides giving a truer record of the actual temperature

of the expanding gas. Over against this it should be stated that the volume of the unheated portions of their bulb and manometer connections, which then constituted the chief source of error in all gas-thermometer measurements, was dangerously large.

Barus obtained 1093° as the melting-point of gold, Holborn and Wien 1072°, a difference of very troublesome magnitude. With these may be compared the earlier value (1045°) obtained by Violle in 1882, and of Callendar (1061°), who extrapolated the readings of the platinum resistance thermometer from the sulphur boiling-point (444.5), where his gas-thermometer measurements ended.

After 1892 Barus turned his attention to other things, but Holborn and Wien published a second article[1] in 1895 confirming and extending their earlier results. By employing a specially refractory porcelain bulb prepared by Dr. Hecht, of the Königliche Porzellan Manufaktur, they were able to continue the gas measurements nearly to the melting-point of nickel, which was determined by extrapolation to be 1484°. Both Barus, and Holborn and Wien, continued the thermo-electric measurements up to the melting-point of platinum, the extrapolation yielding 1780° (Holborn and Wien) and 1855° (Barus) respectively.

Holborn and Day,[2] 1899.—With the advancing demands of science for trustworthy high-temperature measurements, these differences in the absolute temperature of the melting-point of gold, which is an ideal substance for a temperature constant, soon came to be regarded as unsatisfactory and the whole problem was again taken up at the Reichsanstalt by Holborn and Day, with a view to clearing up these differences. At that time the gas thermometer was in serious danger of falling into disrepute as a physical instrument of precision, and it came to be a common habit in meetings of scientific men to excuse particularly poor temperature measurements by remarking that they were made with the gas thermometer. Holborn and Day began by using bulbs of Royal Berlin porcelain, but, after the investigation had proceeded for a year or more, abandoned them definitely and permanently to return to the old platinum bulb of Pouillet, with an appropriate gas (nitrogen) which could not penetrate the bulb wall. A further improvement of inestimable value in attaining constant and reproducible conditions was made when electric heating-coils were substituted for gas. With this change the contamination of the thermo-elements through the action of combustion gases, the danger of one or other of these gases penetrating the bulb wall itself regardless of the character or the pressure of the gas within, irregularities of temperature about the bulb, and inadequate control of the heat supply, were all eliminated or much reduced in magnitude at a single stroke. A preliminary account of these results was published in 1899 and a final account in 1900, in which several metal melting points were established as points of reference for the high-temperature scale, which soon found general acceptance and are still almost universally used.

Barus's Summary,[3] 1900.—At the time of the meeting of the international congress of physicists held in connection with the Paris Exposition in 1900 Barus was invited to prepare a review of the history of pyrometry up to that

[1] Wied. Ann. 56, 360-396, 1895.
[2] Wied. Ann. 68, 817-852, 1899. Am. Journ. Sci. (4), 8, 165-193, 1899.
[3] Rapports présentés au Congrès International de Physique, 1900, vol. 1, 148-177.

time, in which the following table appears. It offers an excellent review of the progress of pyrometry up to that time.

Investigator.	Year.	Silver.	Gold.	Copper.	Nickel.	Palladium.	Platinum.	Iridium.
		°	°	°	°	°	°	°
Prinsep.............	1828	999						
Pouillet.............	1836	1000	1200					
Ed. Becquerel......	1863	960	1092					
Violle..............	1879	954	1045	1054	....	(1500)	(1775)	(1950)
Erhardt and Schertel	1879	954	1075					
Barus..............	1892	985	1093	1097	(1517)	(1643)	(1855)	
Holborn and Wien...	1892	971	1072	1082	(1484)	(1587)	(1780)	
Callendar........*...	1892	(961)	(1061)					
D. Berthelot........	1898	962	1064					
Holborn and Day...	1900	961.5	1064	1084				

Values in parentheses are extrapolated.

To this table Barus's own determinations, which were omitted from the original, and the measurements of Holborn and Day,[1] which were published in the same year just after Barus's paper appeared, have been added. None of the temperatures above the melting-point of copper was determined by direct comparison with the gas thermometer. Violle's higher temperatures were obtained by extrapolation by means of the specific heat of platinum determined for temperatures below 1200°, and Barus's and Holborn and Wien's by continuing the curve of electromotive forces of their thermo-elements over the same range.

Since the beginning of the present century but four attempts have been made to reach 1000° C. with the gas thermometer. These may be taken up in the order of their publication as follows: (1) J. A. Harker (1904), using a porcelain bulb and nitrogen; (2) Jaquerod and Perrot (1905), using a bulb of "quartz glass" and various gases; (3) Holborn and Valentiner (1906) using one bulb of platinum containing 20 per cent of iridium and one of pure iridium, both with nitrogen as the expanding gas; and finally (4) Day and Clement (1908) and Day and Sosman (1910), using bulbs of platinum containing 10 per cent of iridium and 20 per cent of rhodium respectively. The last investigation forms the body of the present paper.

Harker.[2]—The work of J. A. Harker at the National Physical Laboratory (England) does not differ in any important particular from the work of Holborn and Day which immediately preceded it at the Reichsanstalt. His instrument was an exact duplicate of the Reichsanstalt instrument by the same maker (except that the bulb was of porcelain instead of platin-iridium), and has since been altered only in certain minor particulars which need not be recounted here. His experimental operations were painstakingly performed and the results all in substantial agreement with those of Holborn and Day.

Jaquerod and Perrot,[3] *1905.*—Jaquerod and Perrot sought to establish a high-temperature scale from which two of the important sources of uncertainty in previous work should be eliminated: (1) the uncertainty

[1] Ann. d. phys. (4), 2, 505-545, 1900. Am. Journ. Sci. (4), 10, 171-206, 1900.
[2] Phil. Trans. (A), 203, 343-384, 1904.
[3] Arch. d. sci. phys. et nat. d. Genève (4), 20, pp. 28-58, 128-158, 454, 506-529, 1905.

due to differences in the expansion of the various available gases; (2) any uncertainty which might enter the problem through the expansion of the containing vessel (bulb).

To accomplish the first object they prepared with the greatest care quantities of pure nitrogen, oxygen, air, carbon monoxide, and carbon dioxide, and used these successively for determinations of the melting-point of pure gold. To accomplish the second they selected for the material of their bulb a substance whose expansion coefficient was less than one-tenth as great as any which had been employed for the purpose up to that time. Both improvements afforded most valuable information. The five gases with appropriate corrections for their individual pressure coefficients gave the same temperature for gold within very narrow limits of experimental error and the bulb proved impermeable to all the gases and of very low and regular expansion for the temperature range employed. Its limitation lay in the fact that the silica bulb can not be used for temperatures above the melting-point of gold.

The relative accuracy of the individual measurements with this system ($\pm 0.2°$) was perhaps higher than has ever been attained with the gas thermometer,[1] but the absolute value of the gold melting-point which they obtained ($1067°$) is considerably higher than any of the other recent measurements. Whether this is due to some inaccuracy in determining the constants of the (relatively large) unheated connecting space leading to the manometer, or to lack of uniformity in the temperature distribution about the bulb, or to insufficient data about the actual expansion coefficient of the quartz-glass bulb, or perhaps to an unfortunate combination of all of these sources of error, it is impossible for any one except the experimenters themselves to determine. Certain it is that their work has contributed in two most important particulars to relieve the technique of gas thermometry from the uncertainty which has hitherto surrounded it and has thus been of the greatest value to all who have followed or may follow Jaquerod and Perrot.

Holborn and Valentiner,[2] *1906.*—The experiments of Holborn and Valentiner contemplated another definite and important step in advance. Theirs was the first serious effort to extend the gas scale itself from $1150°$ C., where all previous investigations had been halted, to $1600°$ C. The difficulties confronting such an undertaking are obvious and of an insistent kind. Of the limited number of substances available for use as bulbs none is without serious limitations at these extremely high temperatures. Porcelain becomes soft and its walls both absorb and generate gas in prohibitive quantities; silica glass devitrifies; pure platinum is very soft and is permeable to hydrogen; when stiffened with iridium or rhodium it is the best material available; but the iridium is destructive to the thermo-elements, and the bulb is likely to develop leaks and is permeable always to hydrogen if but a trace of the gas or of water-vapor is about. Furthermore, the difficulty of maintaining a constant temperature about a bulb of 200 cc. capacity increases at these temperatures and the difficulty of measuring with thermo-elements within the furnace is greatly increased by the conductivity of all insulating material. It is also a matter of no inconsiderable difficulty to generate and to regulate

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[1] Excepting of course Chappuis, who measured no temperatures above 600°. His magnificent work is therefore hardly within the scope of the present article.

[2] Sitzungsber. Berl. Akad., 1906; 811–817. Ann. d. phys. (4), 22, 1–48, 1907.

accurately the quantity of heat required for a bulb of this size under conditions where all electrical insulation begins to break down, and to protect the mercury manometer from so hot a furnace without removing it to an impracticable distance.

All these reasons and others of inferior magnitude, but often of exasperating pertinacity, contribute to the glory of Professor Holborn's splendid attempt to extend gas thermometry far out into this region, which had hitherto remained inaccessible to all the resources of the laboratory except the somewhat uncertain extrapolation methods. The bulb with which the highest temperature (1680°) was obtained was of pure iridium made for the purpose by that indispensable friend of all recent high-temperature research, Dr. W. C. Heraeus, of Hanau, Germany. It was small, only about 50 cc. in capacity, but held tight through several determinations of temperature reaching nearly to 1700°. The temperatures along the bulb were much less constant than for lower temperatures (differences of 60° on a bulb less than 10 cm. long), and many of the other difficulties noted above no doubt contributed something to influence the result, but the effort demonstrated beyond peradventure that the extension of the gas scale to 1600° is practicable. The result gave melting palladium a temperature of 1575°.

This closes the account of the progress of gas thermometry down to the present undertaking, which was begun in 1904, and so overlaps only the work of Holborn and Valentiner, to which it bears a close relation, as will be explained presently.

3. IMPORTANCE OF ABSOLUTE MEASUREMENTS ABOVE 1150.°

This effort to reach an absolute determination of the temperatures lying between 1200° and 1600° has been chiefly inspired by two conditions. The highest temperatures (above 1600°) are conveniently accessible only to those methods of pyrometry which are derived from the Stefan and Wien-Planck relations, grouped together for convenience under the name "radiation pyrometers." These methods differ among themselves somewhat both in principle and in application, but in general they are all characterized by common qualities. They do not require that the measuring instrument be in contact with the hot body and they are all of very low sensitiveness at the lower temperatures. Furthermore, they are comparatively convenient to use and may be said to have no upper temperature limit. These practical qualities are obviously of inestimable importance to all future pyrometric work, whether in laboratory or industrial practice. Like all other pyrometers, however, they depend for their calibration upon the gas scale and require to have their readings evaluated in terms of it.

Now it happens that these radiation pyrometers do not become effective as temperature-measuring instruments below a bright red heat corresponding to a temperature of perhaps 900° and consequently they overlap the accurately measured portion of the gas scale for purposes of comparison and calibration only in the comparatively short interval lying between 900° and 1150°, above which the radiation scale is often extrapolated beyond 3000°, or more than seven times the interval of measured temperatures. This is obviously very uncertain procedure, the more so perhaps because the

radiation pyrometer is at its lowest sensibility in this 250° region in which the calibration requires to be made. It would therefore add immensely to the stability and trustworthiness of the radiation methods if the gas scale could be extended 200° or 300° farther into the domain of radiation pyrometry with proportionate accuracy. To be sure, we have the thermoelement which overlaps both regions—the gas thermometer from very low temperatures to 1150° and the radiation methods from 900° to the melting-point of platinum (1755°)—but it also depends directly upon the gas scale, and extrapolation beyond this domain is fraught with equally grave uncertainty. Further consideration will be given to this difficulty on a later page (109).

The second reason for making a vigorous effort to extend the temperature-measuring standard to higher temperatures is more directly dictated by the requirements of the researches into the conditions of formation of minerals and rocks upon which this laboratory has now been at work for some years. It happens that the temperature region lying between 1100° C. and 1600° C. is the region in which the most important of the component minerals which go to make up the rocks are first formed, and in which therefore the temperature requires to be defined with great precision in order that the conditions of formation may be accurately known. In fact, a quantitative science of mineral and rock formation becomes possible only when such formation can be studied under known and accurately reproducible conditions, just as the problems of quantitative organic or inorganic chemistry are studied under known temperature conditions. Until very recently the minerals and the ore deposits have never been studied from this viewpoint, and our knowledge of their origin and relation to one another is inferential and very fragmentary when compared with contemporary knowledge of organic and inorganic chemical compounds.

This investigation was undertaken for these two reasons, then:

(1) To provide a broader range of absolute temperatures upon which to develop trustworthy pyrometric methods for general use in the great and increasingly important temperature region lying above 1000°.

(2) To attain much higher accuracy in the study of the conditions of mineral formation than has hitherto been possible.

It is perhaps noteworthy that this second reason for undertaking the present research is the same which inspired the investigation of Barus in 1892, which is in many respects the most comprehensive ever undertaken in this field. It offers additional reasons (if more were needed) why the existing generalizations of physics and physical chemistry should be extended over a wider range of temperatures and pressures. One of the most conspicuous grounds for the delay in attacking many of these obvious and generally recognized problems in geophysics lies in the fact that the measured relations established by the exact sciences have not been of adequate scope to meet the needs of large geologic or petrologic problems. The great body of physical and physico-chemical measurements have been confined to the region between 0° and 100°, while rock formation may have extended over a temperature region reaching to 1500° C. or higher. More embarrassing still is the fact that trustworthy data upon the effect of considerable variations of pressure upon most physical and physico-chemical relations

are altogether lacking. It is therefore by no means certain that the generalizations hitherto regarded as established in quantitative physics and chemistry are directly applicable to problems of geophysical scope.

4. THE EXPERIMENTAL PROBLEM IN GAS THERMOMETRY.

The gas-thermometer problem is one in which theory is often inclined to lose patience with practice. It has been demonstrated over and over again, for example (Barus, loc. cit., Buckingham[1]), that the constant-pressure system of measurement ought to be more direct and free from error than the constant-volume system, notwithstanding which the major portion of the results which go to make up the real progress of the past fifty years has been obtained through the use of the constant-volume principle. Theory has also been very apprehensive from time to time of the ultimate outcome of attempting to define temperature in terms of the expansion of a diatomic gas, and yet nitrogen is the only gas which has yet been found practicable for long ranges extending to the higher temperatures. It does not react with a platinum bulb and does not diffuse through its walls, and so far (up to 1600°) no indication of the dissociation of nitrogen has been found. From the laboratory side of gas thermometry, the main difficulty is now, as it has always been, to find a practicable bulb which will hold some expanding gas without loss or change through a long range of temperatures and permit sufficiently accurate measurements of the pressure-volume relation within. After more than three-quarters of a century of the most varied experiences, pure nitrogen in a platin-iridium bulb in which the pressure at constant volume can be measured, was the only arrangement which had not yet encountered some very serious obstacle to the extension of its range or its accuracy. It was therefore adopted without hesitation for beginning the study here described.

If this somewhat circumstantially selected system does not at the moment appear to confront any insuperable obstacle, many and insidious difficulties have been encountered in the course of its development. One has only to examine the determinations of the same temperature made by different observers, all using substantially this method, to become convinced that some serious work still requires to be done to clear up the present uncertainty. The melting-point of gold is given by Barus (1892) at 1093°; by Holborn and Wien (1895) 1072°; Holborn and Day[2] (1901), 1063.5°; by Jaquerod and Perrot (1905), 1067.2°; by Day and Clement (preliminary, 1907[3]), 1059.1°. For the moment it is sufficient merely to call attention to these differences in the results which have been obtained, and to reserve detailed comment upon them for a subsequent part of the paper. Suffice it to say that both Holborn and Day, at the close of their work (1900) entertained the positive opinion that the discrepancies had occurred in the experimental details and were not chargeable to an oversight in any of the more fundamental relations involved.

With this prevailing idea in mind—that the general relations are already satisfactorily worked out and that the problem remaining is therefore pri-

[1] Bull. Bureau of Standards, 3, 237–293, 1907.
[2] Ann. d. phys. (4), 4, 99–103, 1901. Am. Journ. Sci. (4), 11, 145–148, 1901.
[3] Phys. Rev., 24, 531–532, 1907

marily an experimental investigation, (1) to increase the absolute accuracy of the measurements, and (2) to extend their range—Professor Holborn at the Reichsanstalt and Day and Clement at the Geophysical Laboratory took up the gas thermometer again in 1904. The details were for the most part independently planned and the work has been independently carried out. In a research which offers so many technical difficulties, two independent plants were obviously better than one. In so far as a division of labor was attempted, Professor Holborn entered at once upon the more daring undertaking, namely, to increase the range of measurement. He obtained a bulb of pure iridium in the hope that it might prove possible to make continuous gas-thermometer measurements as far as the melting-point of platinum. For this work the errors of observation were allowed to remain large, larger in fact than they had been in the joint work of Holborn and Day in 1900. The undertaking was entirely successful and yielded very satisfactory measurements up to about 1680°,[1] the error for the new portion of the gas scale (from 1150° on) increasing gradually to about 10° at 1600°.

The work at the Geophysical Laboratory was for the moment restricted to 1200° in an effort to eliminate or materially to diminish the errors which have been inherent in all gas-thermometer measurements up to this time. Progress is necessarily slow in work of this character, but we were chiefly delayed by having to build the entire equipment *ab initio,* except the bulb.[2]

The instrument which we constructed for this work has now been in operation for more than five years. It is of the constant-volume type, as has been explained, similar in general plan to that at the Reichsanstalt, but differing from it in certain important details with the especial purpose of correcting some of the known errors of the Reichsanstalt instrument:

(1) A uniform temperature along the thermometer bulb appeared to us imperative, and a much greater effort was made to obtain it.

(2) The entire furnace was inclosed in a gas-tight bomb in order that a nitrogen atmosphere might be maintained with equal pressures, both inside and outside of the bulb. This had the effect of obviating any tendency of the gas to diffuse into or out of the bulb, and allowed no opportunity for the deformation of the bulb through differences between the pressure within and without. A further effect of this arrangement was to increase the sensitiveness of the instrument fully threefold. It has been the practice heretofore in such temperature measurements to greatly reduce the initial pressure of the gas in order that its final pressure at the highest temperature to be measured may be substantially equal to the atmospheric pressure without, in order that the stress on the bulb through pressure difference may be least when its power to withstand such stress is smallest. In the Reichsanstalt instrument this restricts the available range of pressure for a temperature range from 0°–1150° to about 500 mm. of mercury, or less than 0.3 mm. per degree. By arranging to increase the pressure outside

the bulb as the pressure within increases, this restriction falls away and it is possible to extend the pressure range over the whole length of the scale which the manometer carries. The scale of our instrument was 1.8 meters long. For a range of 1200°, therefore, we were able to work with a sensitiveness of a little more than 1 mm. for each degree centigrade, or rather more than three times the sensitiveness used in the Reichsanstalt instrument, and also to vary the initial pressure considerably without serious loss of sensitiveness. In order to reach 1600° this sensitiveness was subsequently reduced to about three-fourths of a millimeter per degree, which still gives opportunity for measurements of a high order of accuracy.

(3) In the capillary connecting link between the bulb and the manometer, we were able to diminish the volume of the unheated space to about one-third of its former value, and thereby still further to reduce one of the classical errors of gas thermometry. This "unheated space,"[1] it will be remembered, serves to connect the bulb which contains the expanding gas at a certain temperature and pressure with the manometer in which the pressure is measured. This space is therefore filled with gas which forms a part of the total gas content of the bulb, but is not heated with it and therefore requires a correction the magnitude of which has sometimes been so great as to create misgivings about the trustworthiness of the resulting pressure obtained.[2] The ratio of the volume of the unheated space to the total volume of the bulb $\left(\dfrac{v}{V}\right)$ in the final form of the gas thermometer used by Holborn and Day (1900) amounted to 0.0046; in the more recent instrument used by Holborn and Valentiner it amounted to 0.0042 with the 209 cc. platin-iridium bulb and 0.0181–0.0216 with the 54 cc. pure iridium bulb; in the Jaquerod and Perrot apparatus it reached 0.0178; while in our instrument it was reduced to 0.0015. The entire correction for the unheated space in our instrument therefore amounted to less than 4° at 1100° compared with about 20° in the older Reichsanstalt instrument and about 80° in the instrument used by Jaquerod and Perrot. An error of 10 per cent in the determination of the average temperature of the unheated space in our instrument will not therefore affect the result more than 0.4° at this temperature.

(4) The expansion of the bulb itself was redetermined with much greater care than heretofore.

All these are details of the utmost importance if a really accurate temperature scale based upon the expansion of a gas is to be established. The effect of a serious error in any one of the four particulars noted upon the temperature measurement is several times greater than that arising from differences in the expansion of the various available gases which formed the basis of the elaborate study by Jaquerod and Perrot, to which reference has just been made. And here, perhaps, lies the kernel of the whole matter so far as it concerns the establishment of accurate fundamental temperatures in a region as remote as 1000° from the fundamental fixed points. The interest of observers is easily diverted to questions of general and theoretical interest, like the validity of the Gay-Lussac law over great

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[1] "Espace nuisible," "Schadlicher Raum."
[2] See in particular Jaquerod and Perrot, Arch. d. sci. phys. et nat., Genève (4), 20, pp. 28, 128, 454, 506, 1905.

temperature ranges, while experimental conditions which permit errors of considerable magnitude in an absolute scale have had altogether inadequate attention. This is obviously no aspersion upon the beautiful work of Jaquerod and Perrot, or of any other investigator, but it may be the explanation of the prevailing uncertainty in high-temperature measurements. Jaquerod and Perrot, for example, in measuring the melting-point of gold with the gas thermometer, used five different gases successively in the same (fused silica) bulb, and came out with a maximum variation of only 0.4° for the entire series of observations, and yet in its absolute value the redetermination may easily be 5° in error. In fact, in one of their observations in which a porcelain bulb was substituted for silica, a difference of 4° was actually found. The observation was dropped, but it serves to direct attention sharply to a possible uncertainty of several degrees arising from the corrections for the distribution of temperature along the bulb and the unheated space, and for the expansion coefficient of the bulb itself.

5. APPARATUS.

Somewhat more in detail, the apparatus in use at the Geophysical Laboratory may be described as follows:

FURNACE.

The furnace consists of a wrought-iron tube of about 25 cm. inside diameter, carrying a cast-iron pipe flange at each end. To these flanges cast-iron covers were fitted by grinding to a gas-tight joint. In position this bomb is vertical, and the lower cover is permanently secured in place with bolts. The furnace tube is made from a magnesite mixture,[1] is about 36 cm. long and 6 cm. inside diameter, and carries the furnace coil wound on its inside surface. This scheme of winding the heating coil on the inside of a refractory tube is very successful in its operation and is not difficult. With a pure platinum coil (melting-point 1755°) a furnace temperature of 1600° can be reached without danger to the coil and maintained for some time if desired. There is considerable loss of platinum through sublimation in maintaining a resistance furnace at this temperature, so that it is necessary to use a wire of considerable size if it is required to maintain so high a temperature for long periods of time. The gain over the same coil wound on the outside of a thin porcelain tube is about 200° (1600° instead of 1400°) for the same current and conditions of insulation.

The method of winding is simple. A series of five wooden wedges is grouped together so as to collapse when the center one is removed. When grouped and fastened together the outside surface is turned down to a cylinder of exactly the size which the finished coil is to have. This multiple wedge then serves as a collapsible arbor and the coil is wound upon it with any desired arrangement of turns. A piece of paper or thin cardboard between the wire and the arbor sometimes facilitates the removal of the arbor after completing the furnace. The arbor, with the coil upon it, is then placed in position in the cylinder and the remaining space between it and the cylinder wall is filled with magnesite cement of the same composi-

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[1] Harbison-Walker Refractories Co., Pittsburg, Pennsylvania.

tion (plus a little dextrine and water) as the tube itself. When this has set the arbor can be removed, leaving the coil in position in the tube. It then remains merely to go over the exposed wire with a very thin coating of the same cement and the coil is ready for use. Such a coil is less liable to displacement through expansion and contraction than when the winding is on the outside of the tube, for the expansion of the wire, instead of loosening the coils, merely causes them to sit the more tightly in place. We have had such coils in constant use for a variety of purposes in the laboratory for several years, and have found them durable, economical, and most convenient.
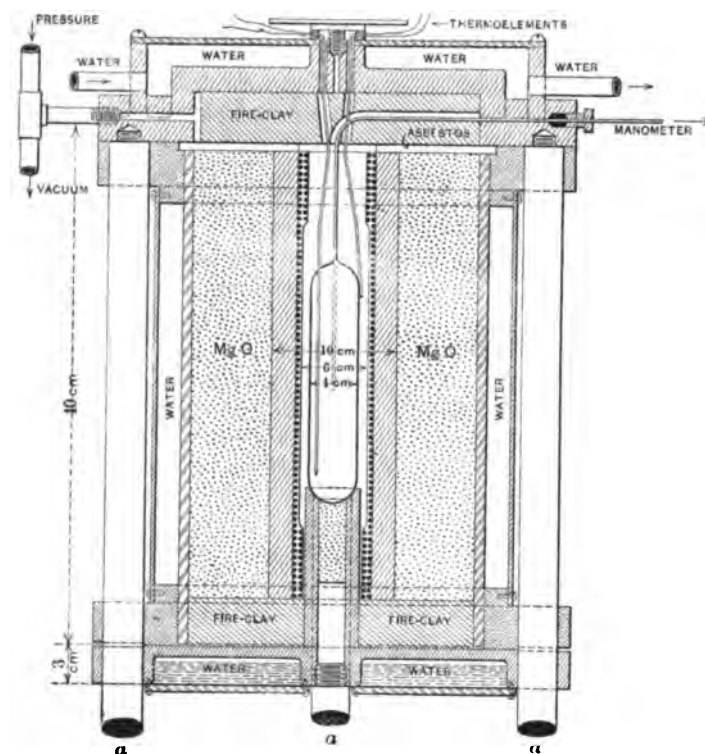
Fig. 1. A section through the gas-thermometer furnace (one-sixth natural size). The bulb is shown in position with the furnace closed ready for heating. The capillary tube connecting with the manometer passes out of the furnace through a packed joint at the upper right-hand corner. The thermo-elements pass through the center of the cover as indicated. The water-jacketing keeps the furnace sufficiently cool so that tight joints are readily obtained with ordinary rubber packing.

In this particular furnace the windings were somewhat closer at the top and bottom of the coil than at the middle, in order to provide a more uniform temperature from one end to the other. This scheme, although efficient, and perfectly satisfactory for most purposes, will not provide a perfectly uniform distribution of temperature over long temperature ranges. An arrangement of the turns which is adequate for low temperatures (500° to 1000°) will not provide sufficient compensation at the ends for much higher ones (1200° to 1600°). We therefore prepared two secondary coils of finer platinum wire in which the current could be independently varied, and
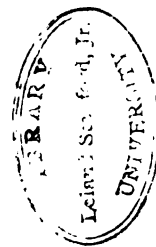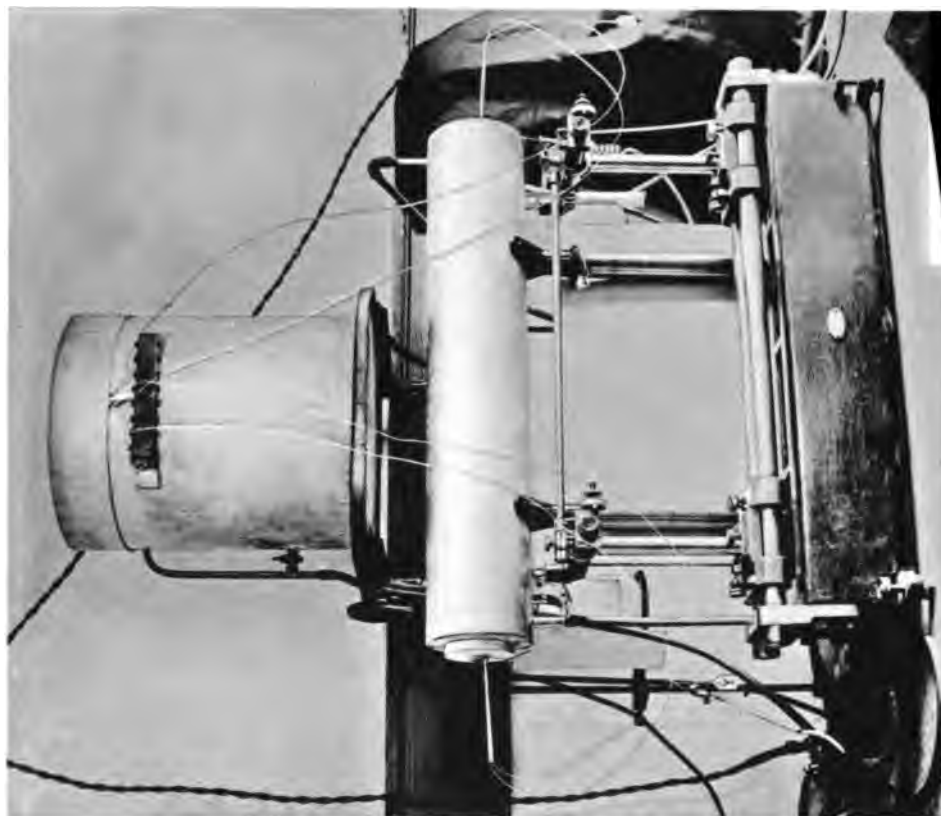
FIG. 3. The expansion apparatus. A photograph of a furnace and accessory apparatus for the determination of expansion coefficients over long ranges of temperature.
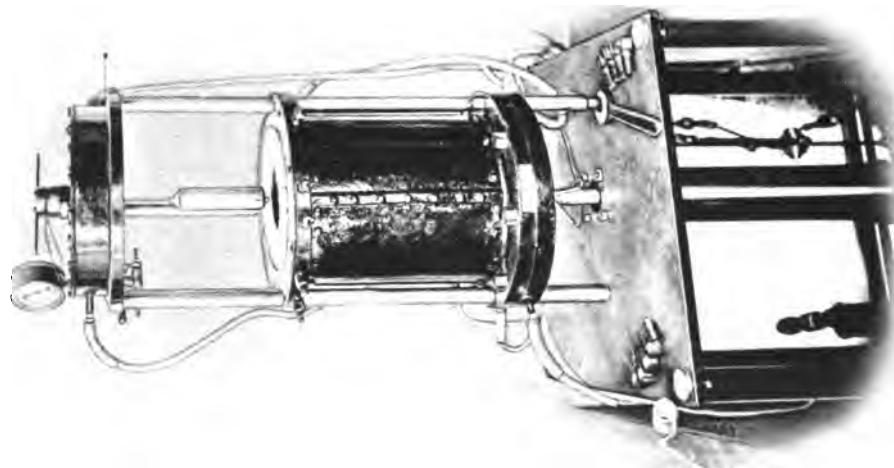
FIG. 2. Photograph of the gas thermometer furnace. The apparatus is shown with the furnace open and ready for the ice-point determination.

mounted them within the main coil at the two ends of the tube. These coils extended into the tube about 7 cm. from each end and were fastened in position by smearing with magnesite cement as before. With this arrangement, we were able to obtain a temperature distribution along the bulb which did not vary more than 2° for any temperatures up to 1550°. To ascertain exactly what the temperature distribution was at the moment of any pressure measurement, it was necessary to use at least three thermo-elements simultaneously, one principal element at the middle of the bulb and secondary elements at each end. These elements were carried out of the furnace between two discs of rubber packing in the center of the cover.

The bulb was symmetrically located in the center of this furnace, the capillary stem extending out at the top of the heating tube and then with a gentle bend of 90° passing out of the metal bomb at the side of the cover, as can be seen in the diagram (Fig. 1). It was then connected by means of a second smaller capillary of platinum with the top of the manometer tube near the point of constant level adjustment. The iron bomb thus prepared was water-jacketed around the sides and at the top and bottom, which effectually prevented any of the furnace heat from reaching the manometer which stood immediately beside it. The scale and mercury columns of the manometer therefore suffered exposure to no temperature variation other than that which existed in the room, and any effect from the variation in the room was easily avoided by inclosing them in tubes of cardboard in which a rapid circulation of air was maintained with a water-jet pump.

When the furnace was mounted in position, the cover, from which hung the thermo-elements and the bulb, was permanently fixed upon three upright steel rods (a a a, Fig. 1). The body of the furnace bomb was then arranged to be lowered away from the cover by sliding upon two of the rods so as to expose the bulb and elements for ice- and boiling-point determinations before and after each heating. Fig. 2 shows the furnace body lowered in this way, leaving the bulb free and completely accessible for arranging an ice bath for the zero reading.

The apparatus is shown with the furnace open and ready for the ice-point determination. Hydraulic power served to raise and lower the furnace conveniently. When the furnace was raised for heating, a circle of bolts provided a positive pressure upon the top joint.

MANOMETER.

The manometer was located about 35 cm. distant from the furnace and was of the usual U-tube type, constructed with a very heavy cast-iron base and light upper parts in order to render the mercury columns as free as possible from the vibrations of the building. The fixed point to which the mercury level was always adjusted occupied the usual position at the top of the short arm, the other arm extending upward for a distance of about 2 meters.

The scale, which was 1.8 meters long, was immediately beside the long tube, and was provided with a sliding vernier reading to 0.01 mm. It was of brass with a silver-plated band upon which the divisions were ruled, and had been calibrated by the German Normal-Aichungs-Kommission in

Charlottenburg. The length of any portion of it was known in terms of the German standard meter to the nearest o.oi mm. The scale was fixed in position below and arranged so as to expand upward through appropriate guides against a rubber cushion with the changes in the room temperature. The long manometer tube also passed through three guide screws at the top of the apparatus, which allowed it to expand and contract unhindered. Readings were obtained by means of two parallel knife edges on the vernier carriage, which could be brought to accurate tangency with the mercury meniscus by a slow-motion screw provided for the purpose. The mechanical construction was extraordinarily rigid and very satisfactory.

The temperature of the scale and mercury columns was obtained from three thermometers, each set in a short tube of mercury after the manner of Holborn and Day.[1] The upper tube with its thermometer could be moved up and down close beside the scale and mercury column, so as to give the temperature of the top of the longest column. The other two thermometers, each in its mercury cup, were fixed in position at the bottom of the long column and the top of the short column respectively. Both columns were surrounded with an inclosed air-tube about 5 cm. in diameter, in which the air was kept constantly and rapidly circulating about both mercury columns. The observed temperature differences along the mercury column sometimes amounted to o.3°. This does not seriously affect the scale length, but the average temperature of the mercury column requires to be known to about o.2°, with the high sensitiveness of this instrument, in order to bring the errors in the pressure determination within the desired limits—hence the three thermometers.

The mercury supply was contained in two basins, one a hollow steel bomb inclosed within the cast-iron base of the instrument, and the other a steel flask mounted upon the wall of the room near the ceiling and connected with the lower reservoir by a flexible iron tube. Cocks conveniently arranged admitted mercury whenever required. The fine adjustment of the mercury level was obtained by pressure upon a nickel diafram which formed the bottom of the lower steel reservoir. This diafram was about 12 cm. in diameter and could be raised slightly by the upward pressure upon its center produced by turning a milled hand-screw convenient to the hand of the operator. The lower reservoir was dome-shaped within and opened into a tube and stop-cock at its highest point, through which any air by chance imprisoned within the reservoir might be allowed to escape.

Gas was admitted to the bulb by means of the three-way cock (A, Fig. 4), leading to a supply of pure nitrogen, the pressure of which could be varied at convenience. It was also possible to exhaust the bulb through the same cock for the purpose of testing for leakage or rinsing the bulb.

UNHEATED SPACE.

From the point of view of the errors of the instrument, the most important part of the manometer is the nickel cap at the top of the short arm which carries the fixed point for defining the constant volume. This cap is sealed into the glass manometer tube with ordinary sealing-wax of good quality, some care being taken that the sealing-wax fills all the cracks, which might

[1] Holborn and Day, " On the gas thermometer at high temperatures," Am. Journ. Sci. (4), 8, 170, 1899.
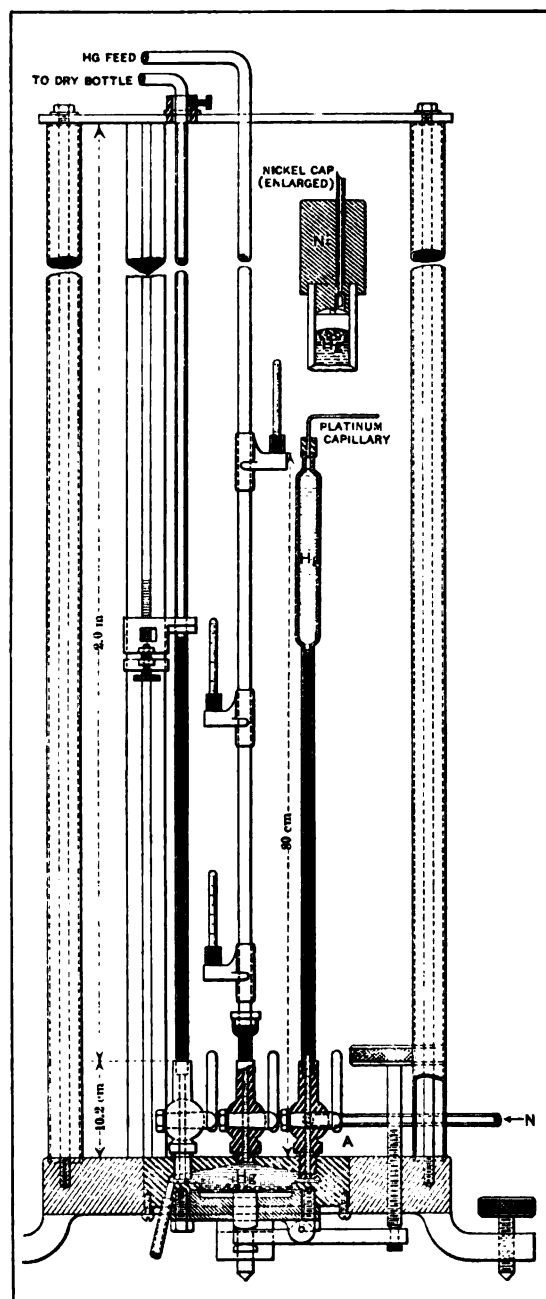
FIG. 4. A diagram of the manometer (about one-eighth size) showing construction and essential features only. Dimensions are approximate.

otherwise retain gas and become a part of the unheated space. The under side of the cap is hollowed out slightly to conform to the shape of the rising mercury meniscus, and in the center a somewhat rounded point of nickel projects downward about 0.3 mm. When the column of mercury is raised in the arm until it becomes tangent to this point, the constant volume of the system is determined. This setting is made through a fixed magnifying microscope of some 20 diameters power. The portion of the "unheated space" included above the column is about 0.3 mm. thick, 1 cm. in diameter, and corresponds in form to the mercury meniscus.

The outlet leading to the bulb is a small opening beside the contact point containing a tiny valve of nickel about 1.5 mm. in diameter and 2 mm. long, with a ground joint at the top, which slides loosely in such a way that, if an accidental rise of the mercury column should tend to drive the mercury over into the bulb, this little nickel plug will be lifted by the mercury and automatically close the opening at the ground joint. This tiny valve opens into the capillary (0.55 mm. in diameter) leading outward to the bulb. Fig. 4 will show the construction more clearly. Where the space above the mercury column requires to be reduced absolutely to minimum volume some such protection is essential. If mercury once passes this opening, through accident or oversight, it reaches the bulb almost immediately, and once there it is a matter of two weeks boiling with nitric acid to get rid of it again.

Even with this valve, it sometimes happened that when gas was bubbled through the mercury in filling, even at the bottom of the tube some 80 cm. distant from the valve opening, tiny globules of mercury were shot upward with such speed and accuracy of aim as to pass up beside the little valve and into the capillary tube, after which their ultimate destination is inevitably the bulb. The altogether insignificant size of the opening and the distance required to be traversed by such a globule did not convey to us a suspicion that a globule might hit and pass it, but it actually happened on two different occasions, with the consequence of an exasperating delay.

In the present arrangement of the gas thermometer, this accident is also provided against by introducing a gold capillary instead of platinum, between the fixed point and the furnace bomb. Such microscopic globules of mercury are taken up by the gold without reaching the bulb and therefore remain harmless.

BAROMETER.

It was deemed advisable from the start not to attempt to combine the barometer with the manometer, as has usually been done by the French observers and latterly in the Reichsanstalt instrument also. It is a convenient method and is rather necessary if a single observer is to make all the readings, but the combination brings three or four essentially different errors into one reading in a way that does not admit of a convenient evaluation of their individual magnitudes.

Two barometers were used throughout this investigation, both of Fuess manufacture and of the same type (Wild-Fuess normal barometer, 14 mm. tube). The corrected readings of the two instruments were in perfect accord and were correct in their absolute value within 0.05 mm.[1]

[1] One of these instruments was compared with the normal barometer at the U. S. Weather Bureau at Washington, the other was compared at the Bureau of Standards

THERMO-ELECTRIC APPARATUS.

The thermo-electric measurements were made with apparatus and by methods which have already been described in varying degrees of fulness in previous publications from this laboratory.[1]

Briefly, it may be noted in passing that all the thermo-electric measurements without exception were made with platinum-platinrhodium thermo-elements of Heraeus manufacture on a potentiometer of Wolff standard construction by direct comparison with a saturated cadmium cell. The cell first used was one of a series described in a previous paper,[2] which has been compared from time to time with the standard cells of the National Bureau of Standards and has never been found to contain an error greater than one or two parts in 100,000. In the later portions of the work other saturated cells courteously furnished by the Bureau of Standards for purposes of comparison were employed, and one Weston unsaturated cell. No errors or discrepancies from this source appeared during the entire investigation.

The galvanometer was a Siemens and Halske instrument of the usual moving-coil type. Later, a more sensitive moving coil galvanometer made by the Weston Electric Instrument Co. was advantageously substituted. With the help of a small rheostat in series with the galvanometer, its sensibility was maintained at a constant value such that one scale division in the telescope (distant 1.5 m. from the galvanometer) corresponded exactly to 1 microvolt in the thermo-element reading, which is roughly equivalent to 0.1°. In these galvanometers the wandering of the needle from its zero position was slight and never amounted to more than 0.2 or 0.3 of a scale division. Both were almost absolutely dead-beat with periods of five and three seconds respectively, so that adjustments for a temperature reading could be made with extraordinary rapidity and with an accuracy out of all proportion to the needs of the experiment.

The only error to which the thermo-electric observations were subject was the contamination arising from the iridium contained in the first bulb. During the first year in which these observations were begun the furnace coil also contained 10 per cent of iridium, but at that time the contaminating effect of this metal upon a thermo-element was not well understood. Later on, this coil was exchanged for a coil of pure platinum made especially for this purpose by Dr. Heraeus, which was guaranteed to contain no more than 0.05 per cent iridium and which was found upon analysis to contain considerably less than this quantity. Inasmuch as the furnace coil is always the hottest part of the system, this afforded considerable relief, but the position of the elements in contact with the bulb made it impossible to prevent some contamination above 900°, so long as the bulb remained bare. An attempt was made to reduce this difficulty still further by the use of a glaze made from melted mineral albite, which was appreciably soft at temperatures of 1100° but which appeared to prevent the sublimation of iridium so long as the coating remained continuous. The viscous material, however,

[1]Day and Allen, The isomorphism and thermal properties of the feldspars, publication of Carnegie Institution of Washington No. 31, 1905. Allen and White, On wollastonite and pseudo-wollastonite, polymorphic forms of calcium metasilicate, Amer. Journ Sci., (4), 21, 89-108, 1906.
Walter P. White, Potentiometer installation, especially for high temperature and thermo-electric work, Phys. Rev., 25, 334-352, 1907. Melting-point determination, Am. Journ Sci., (4), 28, 453-73, 1909; Melting-point methods at high temperatures, Am. Journ. Sci., (4), 28,, 474-489, 1909.
[2]Day and Allen, loc. cit., p. 26.

showed a persistent tendency to gather together into globules, leaving bare spots on the bulb which were not wet by the glaze, so that this protection was not complete. Porcelain insulating tubes open at the ends afford little or no protection. We were accordingly driven to the conclusion that for the higher temperatures iridium must be banished from the furnace completely before consistent observations could be obtained. This is the chief reason why the first series was not extended beyond 1200°. The observations above this temperature will therefore be described on a later page (p. 48). For these later observations a bulb containing no iridium was substituted for the one described here.

Up to 1200° our precautions were sufficient to prevent serious contamination of the elements and the error due to such contamination as was unavoidable has been eliminated by frequent calibrations of the three elements used for each observation, either by comparison with standard elements known to be free from iridium contamination, or by melting-point determinations of standard metals. Toward the close of this first series, in order to establish absolute proof that the readings were not encumbered with systematic errors, however small, from this cause, an independent observation was made in the following way: The element at the middle of the bulb was replaced by a freshly calibrated new element known to be in perfect condition. After an ice-point determination and with all the precautions above described, the furnace was heated directly and as rapidly as possible to 1200°, where a single observation was made and the furnace immediately cooled down again. The new element was then removed from the furnace and recalibrated in order to establish beyond question the fact that it had suffered no contamination whatever during the short and rapid run. This independent determination, in which it was definitely proved that iridium contamination played no part, served to establish the absolute correctness of the high-temperature observations in so far as the error from this most persistent source was concerned.

No reason has yet arisen in any of the experiments with nitrogen for suspecting limitations of any kind due to the gas. It has shown no tendency to react with the platinum bulb or to pass through its wall or to dissociate at any temperature to which it has yet been carried in gas thermometry.

THE BULB.

As has been stated with some emphasis in the historical introduction, the question of a suitable bulb to contain the expanding gas has been and is to-day one of the most serious which gas thermometry confronts. The first experiments (Prinsep) were made with a bulb of gold, which was soon abandoned because of its low melting-point. Following this, platinum was employed (Pouillet), but here a difficulty was encountered which eventually caused its abandonment in favor of porcelain on account of its supposed permeability to gases (Deville and Troost; Becquerel). But the porcelain bulb without glaze is itself porous; with a glaze it is a chemically undefined mineral mixture which not only softens below 1200° with more or less change of volume, but also gives out gas (either original or previously absorbed), so that the porcelain gas thermometer, as it is commonly called, never returns to its original zero after heating to high temperatures.[1] The uncer-

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[1] Holborn and Day, Am. Journ. Sci. (4), 8, p. 185, 1899. Wied. Ann. 68, p. 843, 1899.

tainty in the zero which arises through the use of the porcelain bulb causes an error in a single observation of the order of 5° at 1000°, which is practically impossible of satisfactory correction.

The return to metal bulbs is due to Professor Holborn of the Reichsanstalt, who has successfully used a platinum bulb (containing 20 per cent of iridium) of 200 cc. capacity with nitrogen as the expanding gas up to 1600° without discovering any irregularity in its behavior. A similar bulb of platinum containing 10 per cent of iridium was successfully used in this laboratory for nearly three years without developing any limitation other than that due to the contaminating effect of the iridium on the thermo-elements. It is a matter of great difficulty and some uncertainty to make trustworthy measurements of temperatures above 1000° with platinum thermo-elements in the presence of iridium (see paragraph on thermo-electric measurements preceding), even when the iridium is present only in a low percentage (0.05%) alloy with platinum. To obviate this a bulb of platinum containing 20 per cent of rhodium and no iridium was substituted for the iridium alloy in our later observations (p. 48) with marked success. The porcelain bulb has therefore probably disappeared permanently from gas thermometry.

Parenthetically, it may be remarked that the platinum crucibles and other ware as made up for laboratory use in this country are usually stiffened with about 2 per cent of iridium, a quantity amply sufficient to contaminate thermo-elements if exposed in the furnace with it to temperatures above 900°.

6. PLAN OF PROCEDURE.

The procedure followed in the first series of observations was substantially as follows:

With the body of the furnace lowered so as to expose the bulb, a pail of suitable size was brought up about the latter and filled with distilled water and finely divided ice in such a way as to inclose the bulb and so much of the capillary as was included within the furnace when hot. Several readings of the ice-point were then made on the manometer, together with simultaneous readings of one or both barometers. To control the expansion coefficient of the gas, these readings were occasionally followed by a second reading at the temperature of boiling water in which the ice pail was replaced by a double-chambered boiling-point apparatus of standard type. In general, however, it may be said that the expansion coefficient of pure nitrogen has already been so carefully determined by Chappuis and others that this observation is superfluous, particularly as the sensitiveness obtainable in a bulb of a size suitable for long ranges of temperature is not sufficient to admit of a determination comparable with theirs.

After the ice-point had been determined, therefore, the general procedure was to arrange the thermo-elements in position at the top, middle, and bottom of the bulb (Fig. 1), to close up the furnace gas-tight, and to proceed with the heating. Before turning on the current, however, it was our habit during the earlier experiments to exhaust the bomb and replace the air with a nitrogen atmosphere, the nitrogen being supplied from a separate bomb under high pressure. The nitrogen for this purpose was made in large quantities in the laboratory by the method of Hutton and

Petavel,[1] and pumped into bombs at a pressure of about 1,000 pounds per square inch. One of these bombs could be readily connected with the furnace through appropriate portable connections and a reducing valve whenever desired. Later, compressed air was found to serve the purpose equally well. A pressure gage connecting with the inside of the furnace bomb enabled the pressure within the bomb, that is, outside the bulb, to be read at any time. If the advance in pressure outside the bulb did not proceed as rapidly as that within, additional nitrogen could be admitted if required. In general, it can be said of the operation of this arrangement for the adjustment of pressure within and without the bulb, that if the furnace is perfectly tight the two pressures advance together and are never very far apart. Attention to this detail is therefore not burdensome unless the bomb is leaking, in which case the losses must be supplied by the addition of small quantities of nitrogen from time to time. An effort was made to keep the pressure outside the bulb within one-half pound of the inside pressure as read on the manometer.

After the current had brought the temperature to the point where it was proposed to make a reading, about three-quarters of a hour was required to adjust the three resistance coils so as to produce a permanently uniform temperature along the bulb, which limited the number of temperatures observed in one working day to six or seven. It was therefore our habit to make readings, at 50° or 100° intervals, so as to cover a considerable range of temperatures each day. On following days intermediate temperatures were selected in such a way that the whole field would eventually be canvassed in steps of 25°. In order to provide a sufficiently rigid control of the conditions within the bulb, however, each day's readings began with a new determination of the ice-point.

It is interesting to note in passing that the variation of the ice-point after heating, which was a conspicuous feature in all gas-thermometric work previous to 1900, has now substantially disappeared with the return to the platinum bulb.

When the temperature had become constant over the entire length of the bulb, one observer took his position at the telescope of the manometer and the other at the galvanometer, and simultaneous readings were made of the group of thermo-elements and of the pressure within the bulb. Between each two pressure readings a reading of the barometer was made by the observer at the gas thermometer, the barometer having been arranged in a conveniently accessible position for that purpose. All the readings were arranged in symmetrical groups in such a way that the time rate of change of temperature, if any, would fall out in the arithmetical mean of the pressures and temperatures at the beginning and end of the series. At the beginning and end of this set of observations, readings were made of the three thermometers which gave the temperature of the mercury columns of the manometer. The temperature of the unheated space requires no separate determination, as the average room temperature was sufficiently accurate to determine the correction for the unheated space.

Following such a series, the temperature was increased by the desired interval and the same operation gone through again. Constant attention

[1]Hutton and Petavel, "Preparation and compression of pure gases for experimental work," Journ. Soc. Chem. Ind., 23, 87-93, February, 1904.

was of course required in the meanwhile to see that in increasing the temperature of the furnace, and therefore of the bulb, the pressures inside and outside the bulb did not get too far apart. The same was true of the cooling at the close of the series.

Before the bulb was connected up with the manometer for the final filling, readings were made of the position of the fixed point which defines the constant volume upon the scale. This was done by letting in mercury with both tubes open and reading the mercury level in the long tube when the meniscus in the short tube was raised so as to be just tangent to the fixed point.

Volume of the Bulb.—The volume of the bulb, including the stem, was determined by weighing with water at the beginning of these experiments and again at their conclusion with the following results:

Volume of platin-iridium bulb and stem, September, 1905. . . .   195.79 cc.
Volume of platin-iridium bulb and stem, February, 1908. . . . .   195.66 cc.

Since V_o enters into the computation of temperature only as a part of the correction factor for the unheated space, and as this total correction is never more than $5°$, it is obvious that the absolute volume of the bulb is not, of itself, an important factor in the problem. On the other hand, the correction for the expansion of the bulb with the temperature amounts to $45°$ at $1100°$, and is the most important correction factor which requires to be determined. An error of 1 per cent in the determination of this constant (β) produces an error of $0.5°$ at $1100°$.

7. EXPANSION COEFFICENT OF THE PLATIN-IRIDIUM BULB.

The determination of the expansion coefficient of the bulb did not prove to be the perfunctory operation which had been anticipated, but developed into an independent research of somewhat exasperating character, covering several months.

APPARATUS AND METHOD.

There are two methods which might be pursued to obtain this constant. It is theoretically possible to determine the actual volume expansion of the gas-thermometer bulb in position in the furnace, but an effort to carry it out experimentally a few years ago developed serious difficulties where the range of temperature is so great and the accuracy required so considerable. We therefore preferred to obtain a bar made from the same material as the bulb, and to determine its linear expansion under conditions which were under more perfect control.

In principle, the method of procedure is the one used at the Reichsanstalt. A bar of platin-iridium 5 mm. in diameter and slightly more than 25 cm. in length was prepared for the purpose and heated in a tube furnace in which the temperature could be maintained nearly uniform from one end of the bar to the other and conveniently regulated up to $1000°$ or more. The ends of the bar were filed flat for a distance of 6 mm. and upon these flat surfaces millimeter divisions were ruled with a dividing engine. The balance of the apparatus consisted of a pair of micrometer telescopes mounted so as to observe these divisions and also to maintain a constant

distance between the fixed cross-hairs from beginning to end of the experiment. Heating the bar then served to move the ruled lines past the fixed cross-hairs of the telescopes and the amount of the displacement was measured for any desired temperature.

The aggregate expansion of a 25 cm. bar over the interval from 0° to 1000° is about 2.5 mm. The telescope micrometers as they were focussed for the measurements gave about 450 divisions (each about 2 mm.) of the drum for 1 mm. on the bar, and in the individual readings differences of 0.2 or 0.3 of a division were readily distinguishable. It was therefore easily possible to make very accurate measurements of the expansion of such a bar by direct observation without the use of a contact lever or any multiplying device whatsoever.
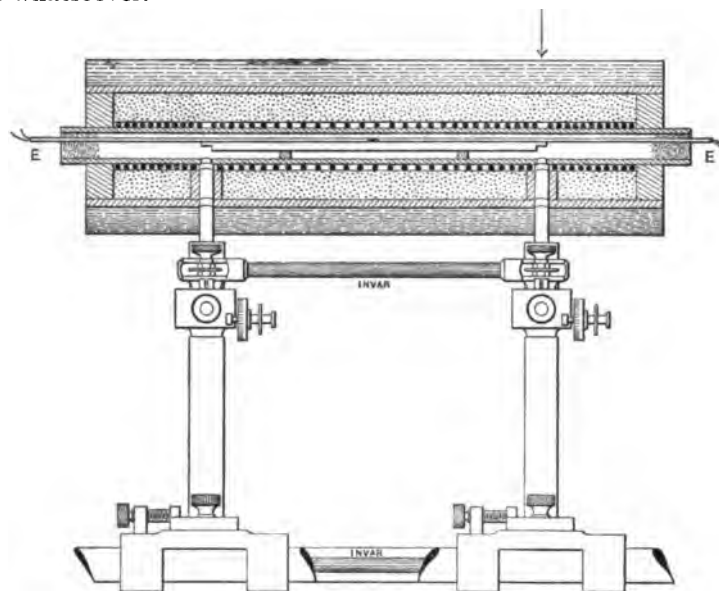
FIG. 5. Longitudinal section of the expansion-coefficient furnace, showing bar, thermo-elements (E, E), and microscopes in position. A section through the arrow is shown in Fig. 6.

The essential features of the apparatus can be partly seen from the figures (Figs. 5 and 6, and Fig. 3, page 19), but require some description. The furnace was erected on a separate stand quite independent of the measuring apparatus. It consisted of a narrow tube wound with a heating coil and containing, opposite the ends of the bar, two small openings through which the divisions could be seen. The inside diameter of the tube was 15 mm. and the side openings were narrow slits about 3 mm. in width by 10 mm. long. The tube and its heating coil extended 10 cm. beyond the ends of the bar and the wire was wound somewhat more closely at the ends than in the middle to counteract the cooling effect of the end and side openings. In this way a reasonably uniform distribution of temperature along the bar was secured.

The first furnace tube was of porcelain wound with nickel wire 1 mm. in diameter, the separate turns being insulated from each other with a mag-

nesite cement which is sufficiently refractory and conducts but little at any temperature which the nickel wire can withstand. Thus arranged, the heating coil was mounted horizontally in a much larger tube (7.5 cm. diameter) of porcelain and the space between filled with dry calcined magnesia of good insulating quality. The whole was water-jacketed throughout in order to prevent any heat from the furnace from entering the optical system and disturbing the fixed distance between the micrometers, upon which the accuracy of the measurement absolutely depends. Both the insulating material and the water-jacket were provided with small openings corresponding to the slits in the furnace tube, so that the bar could be illuminated and observed from without.
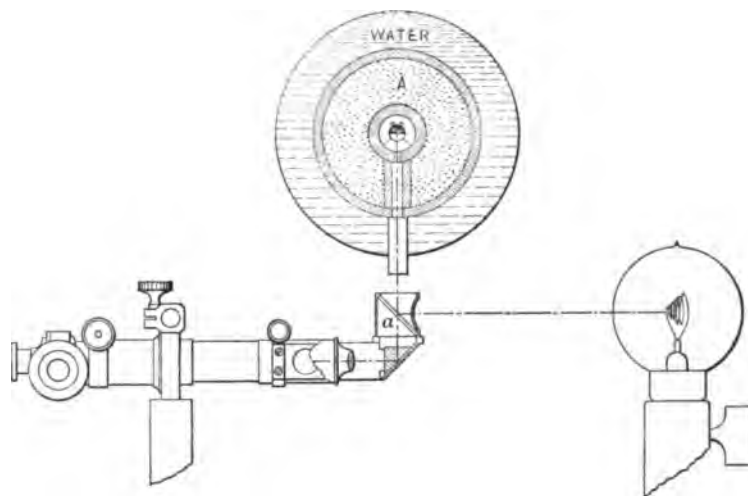
Fig. 6. A transverse section of the expansion-coefficient furnace (A) at one of the openings showing method of illumination by 45° plane glass plate (a). The bar and thermo-element appear in position, though not well shown by this section.

The measuring portion of the apparatus was entirely separate from the furnace and consisted of two telescopes, mounted upon upright brass tubes firmly secured in position upon massive brass carriages which slid freely on horizontal steel guide-bars, 25 mm. in diameter and ground true. The two carriages were then connected by an invar metal bar (Fig. 5), to which they were stoutly and permanently clamped. The whole system was then free to move upon its guides, but the relative position of the telescopes was fixed. The object of this arrangement was obviously to secure a constant distance between the telescopes, in spite of slight changes in the temperature of the system due to changes in the temperature of the room or to the heat from the observer's body, whatever the relative expansion of the various parts of the apparatus. After a good many observations had been made, it was found that the upright brass tubes supporting the telescopes upon their carriages were not uniformly affected by the heat from the body of the observer. They did not therefore expand uniformly and parallel to each other, but tended to buckle very slightly during each series of observations. This was subsequently corrected by a second invar bar above the telescopes, which in combination with the first formed a rugged rectangular

system which preserved the cross-hair distance without change throughout long series of observations.

In mounting the furnace for observation, the side openings which gave access to the scale divisions were directed downward in order to reduce to a minimum the convection currents of air which endanger the constancy of the temperature within. The openings were also made as small as possible for the same reason. It therefore became something of a problem to bring in light enough to illuminate the scale divisions and at the same time to make observations of the change in length with the temperature. The device adopted was this: In the optical axes of the telescopes, and 3 to 4 cm. beyond the objective, small total reflecting prisms were mounted upon the extended telescope tubes in such a way as to deflect the line of sight at right angles and upward into the furnace. Above these prisms and between them and the furnace (see Fig. 6), windows of plane optical glass were set at 45° in such a way that they served to reflect the light from an incandescent lamp upward from their outer surfaces without materially interrupting the line of observation through the telescope and total reflecting prism. By this device the path of the illuminating light was the same as the path of the reflected light which reached the observer, which served to give plenty of illumination for the scale without increasing the size of the openings beyond what was required to see the actual expansion and to measure it.

The illumination was provided by a single incandescent lamp of 100 candle-power with a spiral filament of stock type giving an intense and concentrated illumination. It was mounted behind the furnace 15 cm. distant from the openings, and was so screened by circulating water that its heat did not reach the optical parts of the apparatus save in the two beams which entered the furnace for the illumination of the bar.

The temperature of the bar was determined at first with one thermo-element and afterward with two, which entered the furnace tube from opposite ends in such a way that their hot junctions could be bound together and moved freely along the bar and in contact with it, in order to give a double reading of the temperature at any point desired. In this way we obtained the actual distribution of temperature along the bar corresponding to each determination of its length.

To complete the system, a standard brass bar was prepared of the same size and shape as the platin-iridium bar under investigation, but with silver surfaces let in at the ends to carry the divisions. This bar was compared at 20° C. with the standards of length at the Bureau of Standards, and served to establish the absolute distance separating the cross-hairs before and after each set of observations.

The method of procedure was now substantially as follows: The standard brass bar was placed in position in the furnace at the temperature of the room. All of the necessary adjustments to secure good illumination, to bring the cross-hairs parallel to the scale divisions, and to bring the lines into sharp focus, were then made once for all, and these adjustments were never again disturbed until the series was completed. The field of the microscopes included 5 mm. of the bar, but only the three scale divisions bounding the 2 mm. nearest to the fixed cross-hair were used. Toward the close of the series, for an important reason which will presently appear,

only the two bounding divisions of the single millimeter which included the fixed cross-hair were read and all the observations which had been made outside this limited region were rejected. Readings were made from left to right in each microscope and then repeated in the reverse direction to obviate errors from the micrometer screw. The temperature for this measurement was determined with mercury thermometers thrust into the ends of the furnace tube adjacent to the bar and read before and after the series of micrometer readings. This observation served to establish in absolute measure the distance apart of the fixed cross-hairs of the microscopes. The brass bar was then removed and the platin-iridium bar corresponding to the gas-thermometer bulb inserted in its place in the same relative position. It is necessary here again to emphasize the fact that all further adjustment must be made with the bar and not with the optical parts of the apparatus.

Having brought the bar into exactly the same position with respect to the telescopes which the brass bar previously occupied, and having introduced the thermo-elements in such a way that their hot junctions were free to travel along the bar from end to end without disturbing it, a second series of observations at the temperature of the room was made in the same way as before. This yielded the absolute length of the bar at room temperature in terms of the standard brass bar. The furnace was then ready for heating to the temperature desired.

In the determination of the high-temperature scale carried out at the Reichsanstalt in 1900, four observations of the expansion of the bulb material (250°, 500°, 750°, and 1000°) were deemed sufficient, and it was not thought necessary in our earlier observations to increase this number materially. We therefore began with a 200° interval. After the observation at the temperature of the room, the bar was accordingly heated to 200° C. and sufficient time (about 30 minutes) allowed for the temperature to become constant throughout the furnace, after which a temperature reading was made at the middle of the bar with each element. Observations of length were then made in the same order as before upon the pair of lines adjacent to the fixed cross-hair in each of the microscopes, followed by a second temperature reading at the middle of the bar. After these observations of length and before any change was made in the temperature, nine consecutive pairs of observations were made of the temperature distribution along the bar, first at the center, then on the left section at 5, 10, and 12 cm. out from the middle, then the center repeated; then upon the right section with similar intervals, and again the center, all with both elements. By this means an accurate measurement of the temperature along the bar corresponding to the length measurement just completed was obtained. The whole procedure was then repeated at temperatures of 400, 600, 800, and 1000° C.,[1] after which the furnace was allowed to cool over night and the length of the bar at the temperature of the room was again determined. Immediately following this, an observation of the brass bar was made in order to establish the fact that the distance separating the cross-hairs had not been accidentally disturbed by the manipulation of the furnace during heating.

[1] Subsequently, when we had reason to suspect an irregularity in the rate of expansion, these observations were repeated every 100° and then every 50° in the region between 600° and 1000°.

At 800° and 1000° the bar is self-luminous to a sufficient extent to enable measurements to be readily made without outside light, but it was deemed advisable to use the outside light in the same way at these temperatures also. In passing from outside to inside illumination, the lines are at first dark on a bright ground, and then bright on a dark ground, a change to which the eye accustoms itself only with considerable difficulty. The measurements were therefore much more uniform when outside light was used throughout.

The measurements of the temperature at once encountered the difficulty that the exposure of the thermo-element in the presence of iridium at a temperature of 1000° contaminates it by an amount sufficient to cause a small but cumulative error. This exposure was necessary with the apparatus as we had arranged it, and there was therefore nothing to do but to make the time of the exposure as short as possible, and by the use of two elements fastened together and extending out of the furnace at opposite ends, to so arrange the conditions that any contamination, if sufficient to affect the temperature, would become immediately apparent. As W. P. White of this laboratory has shown in a recent paper,[1] the most critical portion of a thermo-element is not the portion along which the temperature is constant, but the region where the element passes from one temperature to another. In our furnace, for example, the region of exposure to constant temperature could give rise to no error of reading, however much the element might be contaminated in that region, but if a contaminated portion of the element were at any time to come into the region lying between the end of the bar and the outside of the furnace, an immediate difference in its reading should become evident.

It was therefore arranged that the junctions of two elements should be bound together so as to record the temperature of the same point within the furnace and, whenever this combination of two elements was moved toward one end of the bar or the other, that a greater length of one of the elements should be inside the furnace than of the other and a different section of wire be exposed in the transition zone. If there is contamination, a difference in reading between the two elements will then be immediately conspicuous. In the earlier observations comprising this investigation, only one element was used, and by way of control at the close of a long series of observations a second element was introduced in the manner indicated above. It then became immediately evident that the first element had become contaminated and that the observations made with it were affected to a degree which could not be established after the observations themselves were over, and which therefore necessitated the rejection of several entire series. This misfortune may serve to emphasize the necessity of using more than one thermo-element in all cases where it is possible to do so.

Three other difficulties were met with which proved to be sources of considerable inconvenience, and which serve in greater or less degree to place limits upon the accuracy attainable in this particular apparatus. The first was the temperature gradient along the bar, of which mention has already been made. Earlier observers have sometimes been content in similar cases to heat a bar with the electric furnace and to make their measurements upon cold projecting ends, that is, under conditions such that the actual temperature along the bar varies from the temperature of the room

[1] Walter P. White, Phys. Rev. 26, 535-536, 1908.

to a maximum near the middle of the bar. The resulting temperature to which a given measured length is then referred is an integral of a temperature range which varies all the way from that of the room to some point considerably higher than that for which the length measurement is recorded.

This situation seems to us to comport badly with the accuracy otherwise attainable in measurements of this kind, if not to violate fundamental definitions. Unless the expansion coefficient can be treated as linear, such a determination is obviously only an approximation. Furthermore, there is ample precedent for anticipating inversions in an alloy of this character, such that the expansion coefficient of the material below the inversion temperature would differ considerably from that above it. An integration, therefore, in which the temperature range is large may well overlap two physical states in such a way that the length measurement loses all significance. We have not been able to establish the fact that such an inversion exists in the 10 per cent platin-iridium alloy within the temperature range over which these measurements were made, although there is a break in the continuity of the expansion, of small magnitude, which recurs with some persistence, as can be seen from the tables which follow (p. 36 et seq.).

Supposing such an inversion to exist, it would of course follow that the expansion would be a discontinuous function of the temperature, a separate expansion coefficient would need to be determined above and below this point, and the two would not bear any necessary relation to each other. If such a situation exists in the present bar, the difference is so small as to be negligible for our present purpose, but the plain indication of an irregularity led us to appreciate the necessity of maintaining the bar as nearly constant in temperature as possible during the length measurements in order to enable us to interpret the measurements intelligently.

The problem of accomplishing this result gave us considerable anxiety. As has been stated above, the scheme of making optical measurements directly upon the bar without multiplying device of any kind necessarily involves an opening in the furnace coil opposite each end of the bar, and a consequent cooling of that portion of the bar which is opposite the opening. The amount of this cooling, which is greatest at the highest temperatures, reached a value of about 4 per cent in the first furnace coil which we wound. The temperature distribution along the bar is measurable with any accuracy desired by moving the thermo-elements about, or its effective average can be determined by direct integration with a platinum resistance thermometer of equal length, stretched parallel to the bar. We chose the former method on the ground that it yielded more information, and then sought in addition to diminish the irregularity as much as possible for the reason given above. Accordingly, another furnace coil was wound with the turns closer together near the openings. This changed the temperature gradient considerably without materially improving it (see Furnace II, seq.), after which a third coil was prepared with still closer windings, which proved to be considerably overcompensated and was rejected.

In all we made five separate trials of this kind, in the last two of which (Furnaces III and IV) a thick-walled iron tube was substituted for the porcelain furnace tube in the hope of gaining increased uniformity of temperature through the increased heat conductivity of the tube itself. This arrangement succeeded better, but we found it impossible to so arrange a winding

that the temperature opposite the openings was uniform with that at the middle of the tube for all temperatures between o and 1000°.[1] A winding which gave good results at the lower temperatures gave insufficient compensation at the higher ones. The obvious possibility of reaching a uniform distribution, by subdividing the coil into sections in each of which the current could be independently varied was not tried on account of the cumbersome manipulation required, and in part also because the results which we obtained with considerable differences in the gradient appeared to agree very well among themselves.

The temperature carried out in the tables in each case represents the integral of the nine pairs of readings described above. The actual error which enters into an observation from the variation in temperature opposite the openings is therefore the error in establishing this integral, which can hardly be greater than 1° C. or 0.1 per cent.

It will probably occur to other experimenters, as it did to us, that this difficulty with the exposed ends of the bar is due in part to the unavoidable air-currents circulating through the small openings, and that these ought to be checked by the introduction of windows. We made two attempts to reach the difficulty in this way, first using quartz windows set in the opening of the furnace tube itself and therefore heated with the tube; and second, by the use of glass windows set in the water-jacket and therefore outside of the heated zone. The quartz windows behaved very well until high temperatures were reached, when they became displaced by the unequal expansions in the apparatus, thereby causing displacements in the apparent position of the lines of the scale. When the windows were removed to the colder parts of the furnace in order to avoid this displacement, sufficient water-vapor condensed upon them from within to obscure the field, so that the window scheme had to be entirely abandoned.

The second considerable difficulty to be encountered was due to the effect of the outside illumination of the divisions of the bar in a rather highly magnified field (about 25 diameters). Consider the bar to be illuminated by a beam of light from a fixed source which remains constant in position while the bar expands, and the light received through the telescope into the eye to be reflected from the polished parts of the bar surface between the rulings. For reasons which appear in Fig. 7, this reflected light does not show the lines to be equally[2] displaced after expansion. The reason for this is plain after a brief consideration. If lines are ruled with a sharp tool upon soft platinum metal which is afterwards polished to remove the burr left by the cutting tool, the effect is to round off the two edges of each cut to a greater or less extent, and thereby to present approximately cylindrical bounding surfaces to the incident light. The apparent boundary of the line will then be defined by the reflection of this light from the cylindrical surface into the telescope. Now, if this cylinder be moved laterally in the direction produced by the expansion, the light will be reflected from a different point on the cylinder and will therefore show the line in a somewhat different apparent position from that which would be produced by

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[1] A considerable part of the difficulty in correcting the irregular furnace temperature was due to the instability of nickel wire at the higher temperatures. The oxidation is so rapid that a favorable arrangement of the windings, when obtained, does not give uniform results for more than one or two series of observations. It was subsequently abandoned in favor of pure platinum.

[2] The small expansions of the millimeter sections themselves have been taken into account, although not explicitly mentioned in this discussion.

the expansion alone. The drawing is purposely exaggerated to show exactly the character of this optical error.

It was our habit in beginning these observations to select three appropriate lines upon each end of the bar, and to make all the measurements on these, whereupon it was found by a careful examination of the results that the displacement of the three lines after expansion differed systematically by a measurable amount and in a manner which could not be accounted for by the movement of the bar. This difference was very puzzling for a long time, but was finally traced to the source described, and this inference verified by actually moving the bar about in the field in various ways without changing the temperature. The consequence of this discovery was to compel the rejection of all measurements made upon lines other than those immediately adjacent to the fixed cross-hair in the center of the field. The

number of observations at each end was therefore reduced to two, but the agreement of the results was very considerably increased thereby.

The third difficulty is a limitation of the material itself and is therefore not dependent upon the method of measurement. It is the failure of the bar to return to its initial length after heating.

In this particular bar, 25 cm. in length, we actually found differences between the lengths before and after heating of the order of magnitude of 0.02 mm., which varied from one series of experiments to another according as the bar happened to be cooled rapidly or slowly. This quantity is some fifty times larger than the smallest magnitude we could measure, and inasmuch as it depends only upon measurements at the temperature of the room is readily accessible. This limitation of platin-iridium is not sufficient to deprive it of continued usefulness for the gas thermometer. It is the contaminating action of the iridium which distils out of the alloy at all temperatures above 900° in sufficient quantities to eventually destroy the accuracy of the thermo-element, that has led us to abandon the iridium alloy for an alloy of rhodium (see p. 50).

Fig. 7. Showing how the lines appeared displaced after expansion. Actual expansion, *m* to point indicated by the arrow. Apparent expansion, *m* to *n*.

This study of the irregularities present or possible in the expansion of the bulb was pursued much more persistently than is usual in an investigation which is but incidental to a much larger one, on account of the unexpected values obtained. The expansion of pure platinum as determined by Holborn and Day[1] is given by the equation

$$\lambda = (8868t + 1.324t^2)\ 10^{-9}$$

while that of platinum, containing 20 per cent of iridium, made in the same furnace gave

$$\lambda = (8198t + 1.418\ t^2)\ 10^{-9}$$

We had expected, as Holborn and Day assumed in their calculations in 1900, that the expansion of the 10 per cent alloy ought to fall approximately between the two. When it therefore became apparent that our observations were leading to a value, for the 10 per cent alloy, which was of the same

[1] On the expansion of certain metals at high temperatures, Am. Jour. Sci. (4), **11**, 374-390, 1901. Ann. d. phys. (4), **4**, 104-122, 1901.

order of magnitude as that hitherto found for pure platinum, we were for a long time quite unwilling to accept the result. After the close scrutiny of the apparatus and its limitations described above, all of which, either singly or in combination, appeared totally inadequate to account for the unexpected expansion coefficient obtained, there remained the single possibility that some confusion had arisen in the preparation of the bar; but Doctor Heraeus, who made the bar, would not admit this possibility. Even then, it was deemed wise to make a chemical analysis of the bar itself, and this was done by E. T. Allen of this laboratory, with the result that the iridium content was found to be 10.6 per cent. There appears therefore no further alternative but to accept the irregular variation of the expansion with the percentage composition as characteristic of platin-iridium, following the well-known example of the iron-nickel alloys.

EXPERIMENTAL DATA.

TABLE I.—OBSERVATIONS ON THE EXPANSION COEFFICIENT OF THE ALLOY 90 PT. 10 IR.

In Furnace I: Temperature distribution along the bar.

Left.			Middle.	Right.		
			(Corrected temperature.)			
12 cm.	10 cm.	5 cm.		5 cm.	10 cm.	12 cm.
+10°	+11°	+ 7°	287.7°	− 4°	−13°	−15°
+12	+13	+ 7	511.2	− 2	−15	−24
+10	+23	+13	700.	− 5	−21	−30
+28	+33	+17	1044.1	−11	−31	−46

In Furnace I: Expansion.

$$\lambda = \frac{l}{L} = \frac{\text{total expansion}}{\text{initial length}}$$

Equation used for the "calculated" expansions, $\lambda = (8869.5l + 1.3192l^2)10^{-8}$

Date.	Corrected temperature.	λ		Obs.—Cal
		Observed.	Calculated.	
December 30, 1907.....	[1]287.7°	.002635	.002661	−26
	511.2	.004871	.004879	− 8
	712.9	.007051	.006994	+57
December 31, 1907.....	700.0	.006878	.006855	+23
	866.6	.008653	.008677	−24
January 2, 1908........	504.0	.004812	.004805	+ 7
	504.4	.004813	.004810	+ 3
	690.0	.006763	.006748	+15
	689.4	.006755	.006742	+13
	856.5	.008600	.008565	+35
	856.4	.008610	.008564	+46
	1044.1	.010616	.010699	−83
	1043.8	.010635	.010695	−60

[1]Inasmuch as the expansion-coefficient which is here being determined itself enters into the determination of the temperature, the two quantities are not independently variable. The temperatures given above are therefore based upon tentatively assumed constants which have been chosen about where the final values were expected to come. The assumed data are these: melting-point of zinc, 419°; of silver, 960°; of copper, 1083°. With actual temperatures 1° higher or lower, the expansion coefficient would not be affected by an amount equal to one-tenth of one per cent in any part of the curve. The assumed values are, therefore, amply exact for the purpose.

TABLE I—Continued.

In Furnace II: Temperature distribution along the bar.

Left.			Middle.	Right.		
12 cm.	10 cm.	5 cm.	(Corrected temperature.)	5 cm.	10 cm.	12 cm.
−13°	− 1°	0°	294.0°	−4°	−12°	−27°
−22	− 6	− 2	392.0	−6	−20	−41
−28	− 9	− 4	491.0	+2	−17	−33
−30	−13	− 5	592.5	0	−10	−30
−34	−15	− 5	695.0	+4	− 3	−27
−35	−17	− 7	795.0	+8	+ 4	−17
−52	−21	− 9	894.0	+9	+ 6	−12
−51	−21	−10	994.0	+8	+ 8	−14

In Furnace II: Expansion.

Equation used for the "calculated" expansions, $\lambda = (8778.6t + 1.2801t^2)10^{-8}$

Date.	Corrected temperature.	λ Observed.	λ Calculated.	Obs.—Cal.
February 25, 1908......	294.0°	.002679	.002692	−13
	392.0	.003665	.003638	+27
	491.0	.004660	.004619	+41
	592.5	.005632	.005651	−19
	695.0	.006657	.006719	−62
	795.0	.007741	.007788	−47
	894.0	.008848	.008871	−23
	994.0	.010086	.009991	+95

In Furnace III: Temperature distribution along the bar.

Left.			Middle.	Right.		
12 cm.	10 cm.	5 cm.	(Corrected temperature.)	5 cm.	10 cm.	12 cm.
− 2°	− 1°	0°	297.9°	− 1°	− 5°	− 7°
− 6	− 3	−1	397.3	− 1	− 5	− 8
− 9	− 6	−2	496.3	− 1	− 5	− 9
−13	−10	−3	594.3	+ 1	− 3	− 7
−16	−12	−4	646.9	+ 2	− 2	− 6
−16	−12	−4	646.6	+ 2	− 2	− 5
−17	−13	−4	697.0	+ 2	0	− 4
−19	−14	−5	747.8	+ 4	+ 2	− 2
−23	−17	−6	796.3	+ 5	+ 3	0
−27	−20	−7	846.2	+ 6	+ 5	+ 1
−26	−20	−8	897.2	+ 6	+ 8	+ 4
−29	−23	−9	946.6	+ 7	+11	+ 8
−31	−25	−9	1001.5	+11	+17	+14

Table I—Continued.

In Furnace III: Expansion.

Equation used for the "calculated" expansions, $\lambda = (8874.4t + 1.2889t^2)10^{-9}$

Date.	Corrected temperature.	λ Observed.	λ Calculated.	Obs.—Cal.
April 6, 1908...........	297.9°	.002770	.002759	+11
	397.3	.003739	.003730	+ 9
	496.3	.004720	.004723	− 3
	594.3	.005714	.005732	−18
	646.9	.006267	.006283	−16
	646.6	.006262	.006280	−18
April 8, 1908...........	697.0	.006800	.006815	−15
	747.8	.007346	.007360	−14
	796.3	.007897	.007888	+ 9
	846.2	.008445	.008437	+ 8
	897.2	.009013	.009005	+ 8
	946.6	.009579	.009561	+18
	1001.5	.010206	.010187	+19

In Furnace IV: Temperature distribution along the bar.

Left.			Middle. (Corrected temperature.)	Right.		
12 cm.	10 cm.	5 cm.		5 cm.	10 cm.	12 cm.
− 3°	− 2°	0°	299.1°	− 1°	− 4°	− 5°
− 5	− 3	0	399.2	− 1	− 4	− 6
− 9	− 5	− 1	497.0	− 1	− 5	− 7
−14	− 9	− 2	598.3	0	− 3	− 6
−16	− 9	− 3	648.0	+ 1	− 1	− 5
−19	−12	− 4	709.5	+ 3	0	− 4
−21	−15	− 4	748.7	+ 4	+ 2	− 3
−25	−18	− 6	799.1	+ 6	+ 4	− 1
−30	−22	− 7	846.1	+ 7	+ 6	+ 1
−30	−22	− 8	900.4	+ 8	+ 9	+ 4
−36	−26	−10	949.6	+10	+13	+ 7
−36	−27	−11	1000.5	+12	+17	+11

In Furnace IV: Expansion.

Equation used for the "calculated" expansions, $\lambda = (8814.1t + 1.3260t^2)10^{-9}$

Date.	Corrected temperature.	λ Observed.	λ Calculated.	Obs.—Cal.
April 17, 1908...........	299.1°	.002763	.002755	+ 8
	399.2	.003750	.003730	+20
	497.0	.004697	.004708	−11
	598.3	.005702	.005748	−46
	648.0	.006265	.006268	− 3
	709.5	.006889	.006921	−32
	748.7	.007344	.007343	+ 1
	799.1	.007897	.007890	+ 7
	846.1	.008423	.008407	+16
	900.4	.009018	.009011	+ 7
	949.6	.009585	.009566	+19
	1000.5	.010160	.010146	+14

The mean of the equations derived from the observations in the four furnaces, each weighted according to the number of observations in that particular series, is

$$\lambda = (8841t + 1.306t^2)\ 10^{-9}$$

which is the equation used to compute all the gas-thermometer observations made with the platin-iridium bulb.

This interpolation formula is a simple equation of two coefficients obtained by the method of least squares, giving equal weight to all the observations.

Inasmuch as no one of the differences between observed and calculated values reaches 1 per cent in value, this form of equation, which has been frequently employed for the purpose, is perhaps as well adapted to represent the experimental data as another. When it was discovered that the bar after heating did not return to its initial length, but varied within considerable limits from one heating to another, it became apparent that if the contraction upon cooling was not uniform, the expansion on reheating was probably also irregular to the same degree, and that the room temperature observations could not be expected to follow this or any other simple equation very consistently. That such irregularities exist and attain such magnitude as seriously to limit the power of any simple formula to reproduce the expansions over the whole range will be immediately apparent from an examination of the columns of differences (Obs. — Cal.). It is more directly observable in the experimentally determined values of the expansion between o and 300° taken from the four series which have just been given.

MEASURED EXPANSION IN MILLIMETERS BETWEEN 0° AND 300°.

December 30, 1907 . . . . 0.687
February 25, 1908 . . . . 0.681
April 6, 1908 . . . . 0.700
April 17, 1908 . . . . 0.696

By way of experiment we tried an equation of three coefficients on the last two series, both of which contain observations at 50° intervals, omitting in each case the room temperature observation in which the irregularity in the expansion itself chiefly appears, and found it possible to reproduce the measured behavior of the bar in the region from 300° to 1000° with differences less than one-fifth as large as those recorded in the tables above. There is, therefore, abundant evidence that the uncertain region is confined to the lower temperatures and that the higher temperatures have so far offered no serious difficulty or irregularity, either in measurement or convenient representation. The expansion measurements over the entire range from 0° to 1000° may be in error by about 0.5 per cent, most of which is directly attributable to these irregularities in the behavior of the metal at the lower temperatures. In the gas thermometer this corresponds to about 0.25° at 1000°.

8. THE PRESSURE COEFFICIENT OF NITROGEN.

A number of determinations of the pressure coefficient of nitrogen, under different initial pressures, were made by observing the pressure inside the bulb when it was immersed alternately in ice and in steam, with the following results. Values of α obtained by Chappuis are also given.

Day and Clement.			Chappuis.[1]	
No. of observations.	Initial pressure.	a	Initial pressure.	a
4	314 mm.	0.003665	528.8 mm.	0.0036811
5	550	.003668	534.3	.0036846
6	744	.003670	793.5	.0036718o
12	985	.003673	995.9	.0036746́6

9. GAS-THERMOMETER MEASUREMENTS. FIRST SERIES.

COMPUTATION OF RESULTS.

The following formula for the constant-volume gas thermometer was used for the computation of results obtained with the platin-iridium bulb:

$$\frac{pV}{1+at} + \frac{pv_1}{1+at_1} + \frac{pv_2}{1+at_2} = p_0V_0 + \frac{p_0v_1}{1+at'_1} + \frac{p_0v_2}{1+at'_2}$$

In this equation:

V_0 = volume of bulb at $0°$ .... 195.547 cc.

V = volume of bulb at $t.°$

p_0 = initial pressure, i. e., pressure when bulb is at $0°$.

p = pressure at temperature of $t°$.

v_1 = portion of "unheated space" inclosed in furnace (in which temperature varies from the temperature of the bulb to that of the room)............................ 0.161 cc.

v_2 = portion of "unheated space" outside of furnace....... 0.128 cc.

t_1 = estimated mean temperature of v_1 when bulb is at $t°$.

t'_1 = estimated mean temperature of v_1 when bulb is at $0°$.

t_2 = temperature of v_2 when bulb is at $t°$.

t'_2 = temperature of v_2 when bulb is at $0°$.

a = expansion coefficient of nitrogen under constant volume.

β = linear coefficient of expansion of platinum-iridium alloy.

Writing $\quad A = \dfrac{v_1/V_0}{1+at'_1} + \dfrac{v_2/V_0}{1+at'_2}$ and $B = \dfrac{v_1/V_0}{1+at_1} + \dfrac{v_2/V_0}{1+at_2}$

the equation may be transformed into a more convenient form for computation:

$$1+at = \frac{p}{p_0} \cdot \frac{1+3\beta t}{1+A - \frac{p}{p_0}B}$$

$3\beta t$ represents the correction for the expansion of the bulb and $A - \dfrac{p}{p_0}B$ is the correction for the unheated space. In computing p the mercury columns were corrected in the usual manner for temperature and latitude.

[1] Travaux et Mémoires du Bureau International des Poids et Mesures, vols. 6 and 12, 1888 and 1902.

EXPERIMENTAL DATA.

Table II contains some of the earlier results, which were obtained after the temperature gradient along the bulb had been only partially corrected. During this series of observations, the temperature difference between the middle and either end of the bulb varied between 50 and 150 microvolts (5° to 15°). As it was impossible entirely to eliminate the gradient with the arrangement of coils in use at this time, the heating currents were adjusted so as to have the gradients toward the top and bottom of the bulb of opposite sign and of nearly equal value, thereby materially reducing the magnitude of the correction to be applied.

TABLE II.

Initial pressure, 302.3 mm. $a = 0.003665$.
Average temperature difference between middle and either end of bulb, 10°.
Equation used for "calculated" temperatures,
$$t = 50.19 + 0.11176\, e - 1.289 \times 10^{-6} e^2.$$

1906.	p_o	Thermo-couple P.	Temperature observed.	Temperature calculated.	t (obs.)—t (cal.)
	mm.	*mv.*			
April 30..	302.09	3231.[1]	396.8°	397.8°	− 1.0°
		4738.	550.4	550.8	− .4
		6232.	696.5	696.6	− .1
		7302.	797.6	797.5	+ .1
		8428.	900.2	900.5	− .3
		9547.	998.4	999.6	−1.2
		11004.	1123.5	1123.9	− .4
May 1...	302.20				
May 2...	....	2961.[1]	368.6	369.8	−1.2
		4944.	571.2	571.2	.0
		6448.	717.8	717.2	+ .6
		7525.	818.6	818.2	+ .4
		8094.	869.7	870.3	− .6
		9040.	954.5	955.1	− .6
		9750.	1016.4	1017.3	− .9
		10583.[2]	1089.9	1188.5	+1.4
May 3...	302.29				
May 4...	....	3928.	470.0	469.3	+ .7
		5186.	595.2	595.1	+ .2
		5944.	669.1	668.9	+ .2
		6725.	743.8	743.4	+ .4
		7755.	839.7	839.3	+ .4
		9255	973.1	974.1	−1.0
		10135.	1049.9	1050.4	− .5
May 5...	302.30				
May 7...	....	3918.	468.0	468.3	− .3
		6926.	762.8	762.4	+ .4
		8910.	943.4	943.6	− .2
		10631.	1092.8	1092.6	+ .2
		11264.	1147.0	1145.4	+1.6
May 9...	302.52				

Before beginning this series of observations and again after its completion, the thermo-couple P was calibrated by determining its electromotive force at the zinc and copper melting-points. From the results which follow it will

[1] Observations below 400° were not used in computing the parabola.
[2] Temperature fell 2° during observation.

be seen that the electromotive force of the thermo-element, at the temper-
ature of melting copper, has been lowered 15 microvolts (1.2°) through
iridium contamination during the series of measurements:

		Zinc.		Copper.	
April 28, 1906	F.[1]	3398		10488	
	M	3398		10483	
			3398		10486
May 14, 1906	F	3396		10469	
	M	3398		10472	
			3397		10471

After these observations (Table II) the furnace was rebuilt. In place of
the heating coil of platinum-iridium alloy, a coil of pure platinum was sub-
stituted. At the same time the arrangement of the two auxiliary heating
coils was so modified that by proper adjustment of rheostats, the gradient
along the bulb could be reduced to 0.5° or less.

Table III contains a complete series of 76 observations, without omission,
covering a period of more than three months in time, in the order in which
they were made and with the control melting-points through which the
constancy of the thermo-elements was assured.

In order to eliminate, as far as possible, any error due to the contami-
nation of the thermo-couples with iridium, the couples were calibrated from
time to time by metal melting-point determinations. Columns 7 to 10 of
Table III contain the E. M. F's of the standard thermo-couple W for
these calibrations.

As a check against accidental errors of observation, all observations were
made in pairs, with an interval of from 5 to 10 minutes between.

In computing the constants of the equation

$$e= -305.5+8.1749t+0.001654t^2$$

which was used for the "calculated" electromotive forces, the observations
marked * in Table III were omitted in order to equalize the intervals between
points. By comparing the values t (obs.) $-t$ (calc.) (Table III) of the
various pairs of observations, it will be seen that any two determinations at
the same temperature agree within 0.1°. The differences between observed
and calculated temperatures are all considerably less than 1°. The greatest
difference is 0.6°, and the average difference 0.2°.

If we now regroup these observations (Table IV) in the order of increas-
ing temperatures and combine the pairs referred to above, the relation
between the observed and calculated curves appears in a most favorable
light. The average difference in column 6, Table IV, is even smaller than
in Table III and wholly free from systematic variation.[2]

[1] F = Freezing-point. M = Melting-point.
[2] When these observations were first published (Am. Jour. Sci. (4), 26, 405-463, 1908), the "calculated"
values were obtained from the equation

$$t=51.72+0.112499\, e-1.35512 \times 10^{-6}\, e^2$$

and showed systematic variations from the observed temperatures amounting in maximum to 0.7°. This
was interpreted to mean that the simple parabola was no longer adequate to represent the observations
with sufficient accuracy. In a private letter Dr. George F. Becker subsequently called the attention of the
authors to the fact that if the least-square solution were computed with e expressed in terms of t these
systematic differences not only disappeared but a much better agreement (obs.—calc.) was obtained.
Tables III, IV, and V have accordingly been recomputed with Dr. Becker's equation, with the result
that the grounds for apprehension expressed in the previous paper have happily disappeared.

Table III.

All electromotive forces are expressed in terms of thermo-element W. Initial pressure 287.5 mm. $a = 0.003665$. Maximum temperature difference between middle and either end of bulb 0.5°. Equation used for "calculated" electromotive forces:

$$e = -305.5 + 8.1749t + 0.001654t^2.$$

No.	Date	Initial pressure in bulb. (p_0)	Observed temperature gas thermometer.	Observed electromotive force. Element W.	Calculated electromotive force.	Obs.–Calc.	Obs.–Calc.	Constancy of standard thermo-element (W) in terms of metal melting-points. Zinc.	Silver.	Gold.	Copper.
	1907.		°	mv.	mv.	mv.	°	mv.	mv.	mv.	mv.
	Feb. 4							3403			
	Mar. 6	287.55									
1	6		414.49	3367.	3367.1	−0.1	0.0				
2	6		414.96	3371.	3371.5	−0.5	−0.1				
3	6		431.76	3532.*	3532.4	−0.4	0.0				
4	6		432.25	3536.*	3537.1	−1.1	−0.1				
	6	287.39									
5	7		419.96	3416.	3419.3	−3.3	−0.3				
6	7		420.00	3417.	3419.7	−2.7	−0.3				
7	7		436.23	3571.*	3575.4	−4.4	−0.5				
8	7		436.40	3574.*	3577.0	−3.0	−0.3				
9	7		458.55	3789.*	3790.9	−1.9	−0.2				
10	7		458.94	3793.*	3794.6	−1.6	−0.2				
	9	287.34									
11	12		408.51	3309.*	3310.0	−1.0	−0.1				
12	12		408.71	3310.*	3312.0	−2.0	−0.2				
13	12		421.50	3430.	3434.1	−4.1	−0.4				
14	12		421.50	3429.	3434.1	−5.1	−0.5				
15	12		432.83	3540.*	3542.7	−2.7	−0.3				
16	12		432.89	3540.*	3543.3	−3.3	−0.3				
	13	287.35									
	14							F 3405			10461
								M 3404			10461
	14	287.35									
17	15		1078.02	10430.5	10429.1	+1.4	+0.1				
18	15		1077.05	10419.	10417.7	+1.3	+0.1				
	15	287.39									
	16										10463
											10462
19	20		1013.17	9671.	9674.7	−3.7	−0.3				
20	20		1012.43	9664.	9666.1	−2.1	−0.2				
21	20		1079.96	10446.	10451.8	−5.8	−0.5				
22	20		1078.26	10426.	10431.9	−5.9	−0.5				
23	20		1079.02	10434.	10440.8	−6.8	−0.6				
24	20		1032.75	9895.5	9901.0	−5.5	−0.5				
25	20		1032.70	9895.	9900.4	−5.4	−0.5				
	21–22							F 3405			10457
								M 3405			10456
	23	287.55									
	Apr. 2–3							F 9046		10214	10454
								9046		10214	10454
	22	287.51									
26	23		416.14	3383.	3382.8	+0.2	0.0				
27	23		416.26	3384.	3384.0	0.0	0.0				
28	23		520.07	4393.	4393.3	−0.3	0.0				
29	23		519.71	4388.	4389.8	−1.8	−0.2				
30	24		489.79	4095.	4095.2	−0.2	0.0				
31	24		489.89	4097.	4096.2	+0.8	+0.1				
32	24		588.00	5073.5	5073.1	+0.4	0.0				
33	24		587.97	5072.5	5072.8	−0.3	0.0				

*In computing the constants of the equation at the head of Table III, the observations marked * were omitted in order to equalize the intervals between points.

TABLE III—Continued.

No.	Date	Initial pressure in bulb (p_0)	Observed temperature gas thermometer.	Observed electromotive force. Element W.	Calculated electromotive force.	Obs.−Calc.	Obs.−Calc.	Constancy of standard thermo-element (W) in terms of metal melting-points.			
								Zinc.	Silver.	Gold.	Copper.
	1907.		°	mv.	mv.	mv.	°	mv.	mv.	mv.	mv.
34	Apr. 24	....	688.44	6104.	6106.2	−2.2	−0.2	....	....		......
35	24	....	687.84	6099.5	6100.0	−0.5	0.0	....	....		......
	25	287.56	....								
36	26	....	550.81	4700.5	4699.1	+1.4	0.1	....	....		
37	26	....	550.65	4698.	4697.5	+0.5	0.0	....	....		
38	26	....	769.49	6962.	6964.2	−2.2	−0.2	....	....		
39	26	....	768.86	6957.5	6957.5	0.0	0.0	....	....		
40	26	....	866.45	8020.5	8019.2	+1.3	+0.1				
41	26	....	867.99	8029.	8036.2	−7.2	−0.6				
42	27	....	644.34	5648.	5648.5	−0.5	−0.1	....	....		
43	27	....	644.24	5646.	5647.5	−1.5	−0.1	....	....		
44	27	....	957.20	9036.	9034.8	+1.2	+0.1	....	....		
45	27	....	958.81	9054.	9053.0	+1.0	+0.1	....			
46	29	....	451.00	3718.	3717.8	+0.2	0.0	....	....		
47	29	....	450.76	3716.	3715.5	+0.5	+0.1	....			
48	29	....	1057.32	10190.5	10186.7	+3.8	+0.3	....			
49	29	....	1057.09	10188.	10184.1	+3.9	+0.3	....			
	29	287.55	....								
	May 1–10		....			....		F 3400	9046	....	
								M3400	9050		
50	13	....	421.19	3430.	3431.1	−1.1	−0.1	....			
51	13	....	422.06	3438.5	3439.4	−0.9	−0.1	....			
52	13	....	751.52	6771.5	6772.1	−0.6	−0.1	....			
53	13	....	751.36	6769.5	6770.4	−0.9	−0.1	....			
54	14	....	663.62	5845.5	5847.8	−2.3	−0.2	....			
55	14	....	663.33	5848.	5844.8	+3.2	+0.3	....			
56	14	....	978.10	9274.	9272.5	+1.5	+0.1	....			
57	14	....	978.82	9281.	9280.7	+0.3	0.0	....			
58	16	....	571.49	4907.	4906.5	+0.5	+0.1	....			
59	16	....	571.37	4906.	4905.3	+0.7	+0.1	....			
60	16	....	795.42	7242.	7243.3	−1.3	−0.1	....			
61	16	....	795.46	7243.	7243.7	−0.7	−0.1	....			
62	16	....	795.24	7240.	7241.4	−1.4	−0.1	....			
63	16	....	1056.91	10188.	10182.0	+6.0	+0.5	....			
64	16	....	1056.15	10177.	10173.1	+3.9	+0.3				
65	17	....	710.27	6338.	6335.2	+2.8	+0.3	....			
66	17	....	710.70	6341.	6339.7	+1.3	+0.1	....			
67	17	....	888.96	8272.	8268.5	+3.5	+0.3	....			
68	17	....	889.50	8277.	8274.5	+2.5	+0.2	....			
69	17	....	955.74	9024.	9018.2	+5.8	+0.5	....			
70	17	....	955.01	9015.	9009.9	+5.1	+0.5	....			
71	18	....	468.56	3891.	3888.0	+3.0	+0.3	....			
72	18	....	468.94	3894.5	3891.7	+2.8	+0.3	....			
73	18	....	839.95	7730.	7727.8	+2.2	+0.2	....			
74	18	....	839.46	7725.	7722.4	+2.6	+0.2	....			
75	18	....	930.70	8741.	8735.4	+5.6	+0.5	....			
76	18	....	930.62	8740.	8734.5	+5.5	+0.5	....			
	19	287.63	....		....			....			
	20–22		....		....			F 3398	9040	10212	......
								M3398	9040	10216	
	23		....		....			F 9042		....	......
								M9042			

TABLE IV.

$$e = -305.5 + 8.1749\ t + 0.001654\ t^2.$$

Number of observation.	Observed temperature, gas thermometer.	Observed electromotive force, element W.	Calculated electromotive force.	Obs.– Calc.	Obs.– Calc.
	°	mv.	mv.	mv.	°
1, 2, 5, 6, 13, 14, 26, 27, 50, 51.	418.97	3407.7	3409.9	−2.2	−0.2
46, 47	450.88	3717.0	3716.6	+0.4	0.0
71, 72	468.75	3892.8	3889.9	+2.9	+0.3
30, 31	489.84	4096.0	4095.7	+0.3	0.0
28, 29	519.89	4390.5	4391.6	−1.1	−0.1
36, 37	550.73	4699.3	4698.3	+1.0	+0.1
58, 59	571.43	4906.5	4905.9	+0.6	+0.1
32, 33	587.99	5073.0	5073.0	0.0	0.0
42, 43	644.31	5647.0	5648.2	−1.2	−0.1
54, 55	663.48	5846.8	5846.4	+0.4	0.0
34, 35	688.14	6101.8	6103.1	−1.3	−0.1
65, 66	710.49	6339.5	6337.5	+2.0	+0.2
52, 53	751.44	6770.5	6771.3	−0.8	−0.1
38, 39	769.18	6959.8	6960.9	−1.1	−0.1
60, 61, 62	795.37	7241.7	7242.8	−1.1	−0.1
73, 74	839.71	7727.5	7725.1	+2.4	+0.2
40, 41	867.22	8024.8	8027.7	−2.9	−0.3
67, 68	889.23	8274.5	8271.6	+2.9	+0.3
75, 76	930.66	8740.5	8734.9	+5.6	+0.5
44, 45, 69, 70	956.68	9032.2	9028.9	+3.3	+0.3
56, 57	978.46	9277.5	9276.6	+0.9	+0.1
19, 20	1012.80	9667.5	9670.4	−2.9	−0.3
24, 25	1032.73	9895.3	9900.8	−5.5	−0.5
48, 49, 63, 64	1056.87	10185.9	10181.5	+4.4	+0.4
17, 18, 21, 22, 23	1078.31	10430.0	10432.5	−2.5	−0.2

In their paper on the electromotive force of metals of the platinum group, Holborn and Day[1] have shown that the relation between the thermo-electric force and the temperature could be represented, within wide limits, with an accuracy of $\pm 1.0°$ by a function of the second degree. The results of our measurements are represented by a function of the second degree, between 400° and 1100°, with an average error somewhat less than 0.2°, the maximum error reaching 0.5° in two cases.

After the series of observations represented by Tables III and IV, the bulb was evacuated and refilled with nitrogen under a somewhat higher initial pressure, $p_0 = 325$ mm. With this filling, the results contained in Table V were obtained. Column 5 of this table contains the differences between the observed electromotive forces and the electromotive forces calculated with the equation:

$$e = -265.6 + 8.0784\ t + 0.0017124\ t^2.$$

The average difference is 0.16°, the maximum difference 0.5°.

[1] Am. Journ. Sci. (4). 8, 303–308, 1899.

TABLE V.

Thermo-couple *W*.　　Initial pressure 325 mm.　　*a* = 0.003665.
Equations used for calculated temperatures:

$$e = -265.6 + 8.0784t + 0.0017124t^2$$
and $e = -305.5 + 8.1749t + 0.001654t^2$ (last column parentheses).

Date.	Observed temperature, gas thermometer.	Observed electromotive force, element *W*.	Calculated electromotive force	Obs.—Calc.	Obs.—Calc.
1907.	°	*mv.*	*mv.*	*mv.*	°
June 3...	482.10	4025.	4027.0	−2.0	(+0.5)−0.2
	482.15	4026.	4027.5	−1.5	(+0.6)−0.1
	581.29	5009.	5008.9	+0.1	(+0.4) 0.0
	582.22	5017.5	5018.2	−0.7	(+0.3)−0.1
	675.07	5974.	5968.3	+5.7	(+0.7)+0.5
June 4...	700.88	6238.5	6237.6	+0.9	(+0.2)+0.1
	701.05	6239.	6239.4	−0.4	(+0.1) 0.0
June 6...	772.10	6992.	6992.6	−0.6	(0.0)−0.1
	771.72	6988.	6988.5	−0.5	(0.0) 0.0
May 29..	819.00	7495.	7499.2	−4.2	(−0.4)−0.4
June 4...	860.52	7954.	7954.0	0.0	(−0.2) 0.0
	860.47	7952.	7953.5	−1.5	(−0.1)−0.1
June 5...	908.47	8488.5	8486.7	+1.8	(+0.2)+0.2
	908.57	8488.5	8487.8	+0.7	(+0.1)+0.1
June 4...	955.30	9016.	9014.4	+1.6	(+0.3)+0.1
	954.91	9011.	9010.0	+1.0	(+0.2)+0.1
June 5...	995.32	9474.	9471.4	+2.6	(+0.5)+0.2
	995.86	9480.	9477.6	+2.4	(+0.4)+0.2
June 6...	1038.82	9975.	9974.3	+0.7	(+0.3)+0.1
	1035.65	9940.	9937.5	+2.5	(+0.5)+0.2
	1058.50	10197.5	10204.0	−6.5	(−0.3)−0.5

The agreement between this series of observations (Table V) and the preceding one (Tables III and IV) is also remarkably close. Perhaps this is best shown by the fact that the same equation used for the "calculated" values in Tables III and IV will represent the observations of Table V also with ample accuracy for purposes of interpretation. These differences are carried out in parentheses in the last column as an added evidence of the general agreement of all the experimental results. It will be remembered that the initial gas pressure and therefore the sensitiveness of the instrument, together with all the correction factors which depend upon it, were changed for the observations of Table V.

MELTING-POINTS BASED ON FIRST SERIES (PT-IR BULB).

Four metal melting-points were used to fix the gas-thermometer temperatures of the preceding tables—zinc, silver, gold, and copper. Analyses of the metals are given on page 85. The melting-point determinations (except gold, of which the only sample then available accidentally became contaminated with iron during the observations and could no longer be used as a standard) are contained in Table VI.

TABLE VI.—TEMPERATURE OF FIXED POINTS.

FIRST SERIES, PLATIN-IRIDIUM BULB.

ZINC.

Number (from Table III).	Date.	Element W in gas-thermometer furnace.	Gas-thermometer temperature.	Element W in zinc bath.	Observed temperature of melting zinc.
	1907.	mv.	°	mv.	°
1	Mar. 6	3367.	414.49	3405.	418.5
2	Mar. 6	3371.	414.96	3405	418.5
5	Mar. 7	3416.	419.96	3405.	418.8
6	Mar. 7	3417.	420.00	3405.	418.7
13	Mar. 12	3430.	421.50	3405.	418.9
14	Mar. 12	3429.	421.50	3405.	419.0
26	Apr. 23	3383.	416.14	3405.	418.4
27	Apr. 23	3384.	416.26	3405.	418.4
50	May 13	3430.	421.19	3400.	418.0
51	May 13	3439.	422.06	3400.	418.0

Melting-point of zinc (Pt-Ir bulb)—Mean.......... 418.5°
Average error................................... 0.3°

SILVER.

44	Apr. 27	9036.	957.20	9045.	958.0
45	Apr. 27	9054.	958.81	9045.	958.1
56	May 14	9274.	978.10	9045.	958.1
57	May 14	9281.	978.82	9045.	958.2
69	May 17	9024.	955.74	9042.	957.3
70	May 17	9015.	955.01	9042.	957.4
—	June 4	9016.	955.30	9042.	957.6
—	June 4	9011.	954.91	9042.	957.6

Mean... 957.8°
Average error.................................... 0.3°
Approximate correction for loss of heat at ends of bulb. +2. °

Melting point of silver (Pt-Ir bulb)............. 960°

COPPER.

17	Mar. 15	10430.5	1078.02	10461.	1080.5
18	Mar. 15	10419.	1077.05	10461.	1080.5
21	Mar. 20	10446.	1079.96	10456.	1080.9
22	Mar. 20	10426.	1078.26	10456.	1080.8
23	Mar. 20	10434.	1079.02	10456.	1080.9

Mean... 1080.7°
Average error.................................... 0.2°
Approximate correction for loss of heat at ends of bulb. +2. °

Melting-point of copper (Pt-Ir bulb)............ 1083°

This work with the platin-iridium bulb developed two serious limitations which have received detailed consideration and correction elsewhere (pp. 50 and 51). They are these:

(1) Independent end coils wound on the furnace tube (see Fig. 1) can be made to give perfectly uniform temperature distribution along the sides of the bulb from end to end, but not on the end surfaces.

(2) The sublimation of the iridium in the bulb, while not prohibitive below 1100°, affects the homogeneity of thermo-elements during the exposure necessary to calibrate them, at temperatures above 900°, to an extent which greatly limits their subsequent usefulness.

This second limitation led to the substitution of a bulb containing rhodium in place of iridium, but does not seriously affect the results already obtained with the platin-iridium bulb, which were all below 1100° (Tables III, IV, V). The first limitation, on the other hand (the cooling of the end surfaces of the bulb by radiation), was not detected until the observations with the platin-iridium bulb were completed and published and the bulb itself was returned to the maker. It is therefore no longer possible to supply a correction factor made with the same bulb under identically the same conditions with which to compensate the error in the final temperatures of Table VI. The new platin-rhodium bulb, however, except for the reentrant tube below, was of the same dimensions as the old one and the furnace conditions were very closely reproducible. A measurement was accordingly made with the new bulb as nearly as possible under the conditions previously employed and another with a diafram in the tube to cut off and reflect back the radiation going out from the upper end of the bulb. The temperature was that of melting copper (1082.6°). This diafram above the bulb raised the gas thermometer temperature 0.9°. A similar test for the effect of radiation from the bottom could not be made, but it was probably of similar magnitude. The total error incurred in the above measurements through the radiation from the ends of the bulb would therefore be of the order of magnitude 2° at the copper-point. At low temperatures the effect is too small to make it worth while estimating a correction factor. If we then suppose the radiating power of the 20 per cent platin-rhodium alloy to be comparable with that of the iridium alloy, one may apply this correction to the mean temperatures obtained with the platin-iridium bulb as given in Table VI. While these values are in good agreement with the later results obtained with the platin-rhodium bulb, they are not included in Table XIX because of the approximative character of this ex-post-facto correction.

10. INTRODUCTION TO THE SECOND SERIES, INCLUDING THE HIGHER TEMPERATURES, 1100°–1600°.

Above 1100° considerable uncertainty has existed in the temperatures of various fixed points. The melting-point of nickel, determined by extrapolation from the data of Holborn and Wien (1484°),[1] has been frequently employed. The curve of the platinum-platinrhodium thermo-element, extrapolated beyond the copper-point, has been still more generally used, but like most extrapolations, may lead to quite erroneous results. The only gas-thermometer comparison that has been made in this region is that

[1] Holborn and Wien, Wied. Ann. 47, 107–134, 1892; and 56, 360–396, 1895.

of Holborn and Valentiner,[1] but by their own estimate the accuracy of the upper portion of their scale is not greater than ± 10°. The chief purpose of our work was, therefore, to establish the temperature of several fixed points between 1100° and 1600° and to ascertain what curve is followed by the platinum-platinrhodium thermo-element in this region, with an accuracy comparable to that obtained in the lower portion.

The plan of procedure is simple. It consists, first, in selecting certain fixed thermometric points, usually melting-points of metals, and in determining their reproducibility; second, in making a measurement of the true temperature on the nitrogen scale at or close by these fixed points; third, in transferring these known temperatures by means of a thermo-element over to the fixed points selected. This transference by the thermo-element is necessary because the thermometer bulb can not be put directly into melting or solidifying substances at high temperatures. The relation of electromotive force to temperature for any particular kind of thermo-element does not enter into the problem when the temperatures measured are close to the fixed points; a linear correction is then abundantly accurate. The interpolation curve, for any element, between the fixed points established by the gas thermometer is therefore a separate matter.

No other method of transferring the gas-thermometer temperatures can be employed in this region. Of the two methods of comparative temperature measurement in common use, one, the platinum resistance pyrometer, can not be used above 1100° with certainty—the other, the radiation pyrometer, is of wholly inadequate sensitiveness in any of the forms hitherto devised.

The questions which remain to be answered are, then: (1) How exact and uniform can the temperature of the gas in the bulb be made (independently of any effort to measure this temperature)? (2) How accurately can its pressure be measured in order to establish that temperature on the nitrogen scale? (3) How accurately can this temperature be transferred from the thermometer and compared with the fixed melting-point? (4) How accurately can the fixed points be reproduced for purposes of calibration of secondary measuring devices?

As has been stated, our experience has convinced us that most of the variations in the gas-thermometer temperatures of the fixed points commonly used by various observers, are due, not to differences in the properties of different gases, nor to differences in pressure, nor to differences between the constant-volume and constant-pressure scales, all of which have been frequently discussed from the theoretical standpoint; but to systematic errors residing in the apparatus and the methods employed. A large portion of the present work has therefore been devoted to finding out experimentally the effect of variations in all those conditions which might affect the results systematically.

[1] Ann. d. phys. (4), 22, 1-48, 1907.

II. CHANGES IN THE APPARATUS.

In all essentials the gas-thermometer apparatus used for this second series of measurements is identical with that already described, except for the bulb.

THE PLATIN–RHODIUM BULB.

Primarily and obviously, the bulb must be able to hold the expanding gas without absorbing or losing any portion of it throughout the temperature range of the measurements. A secondary requirement, the importtance of which increases rapidly when high accuracy is sought, is that it shall be possible to use several thermo-elements in the furnace with the bulb without their readings being endangered by contamination from the bulb material. As long as this intermediary role of the thermo-element remains a necessary one and alloys of platinum continue to provide the only successful bulb material, the contamination[1] of the platinum wire of the element by the alloyed iridium or other platinum metal in the bulb will remain a serious consideration in all temperature measurement above 900°.

Although the platin-iridium bulb served well as a gas-container, the contaminating effect of the iridium upon the thermo-elements made the life of the latter, for measurements of this degree of accuracy, very short. Accordingly, at the close of the first series of experiments, a change was made from the platin-iridium bulb to one of platin-rhodium (80 parts platinum, 20 parts rhodium) 160 mm. long and 47 mm. in diameter. Inasmuch as one of the wires of the thermo-element itself contains 10 per cent of rhodium to which the platinum wire is always exposed (and which gradually contaminates it, too, although very slowly[2]), it was thought that the substitution of a rhodium alloy in the bulb might serve to retain the necessary qualities of stiffness and regularity of expansion with a minimum of disadvantage in the matter of contamination. These expectations have been completely realized. Although the rhodium alloy is less rigid at temperatures of 1000° and beyond than the iridium alloy, and requires more careful adjustment for equal pressure within and without, no sagging of the bulb walls or deformation from the gas pressure has appeared up to 1550°. Meanwhile, the contamination of the thermo-elements in the presence of the rhodium alloy is now reduced to about 20 per cent of its former magnitude for a given temperature and time of exposure.

THE FURNACE.

The common practice of recent observers (Callendar, Harker, Holborn and Day, Jaquerod and Perrot) has been to use a cylindrical bulb in which the length was three or four times the diameter, inclosed in a concentric furnace tube (air-bath) heated by the electrical resistance of a coil of wire wound upon or within it. To this bulb the heat is applied radially over its cylindrical surface, but no heat is supplied at the ends. The furnace tube itself and the winding of the coils have been changed at different times and in a variety of ways in order to vary the distribution of the heat supply. The arrangement which has become usual with us is to wind the coil somewhat more closely at the ends than the middle, with the idea of providing

[1] For a detailed account of the behavior and treatment of contaminated thermo-elements, see Walter P. White, Phys. Rev., **23**, 449–474, 1906.

[2] White, "Constancy of thermo-elements." Phys. Rev., **23**, 463–465, 1906. Phys. Zeitschr., **8**, 331–333, 1907.

partial compensation for the inevitable heat losses at the ends of the furnace in this way, and, in addition, to insert supplementary coils of smaller wire in the ends of the furnace tube in order to provide a small, independently regulated heat supply which can be superposed upon that of the main coil and give the desired uniformity at any temperature likely to be employed. A furnace tube arranged in this way, except for accidental variations, caused, for example, by the flaking off of the furnace lining, affords uniform temperature distribution over a length of 20 cm. in the center of the tube for a range of temperature from 300° to 1550°, and no one temperature is more difficult to regulate than another. This arrangement contains a limitation, however, of considerably greater magnitude than was at first suspected. The ends of the bulb face the comparatively cold ends of the furnace tube and radiate a sufficient quantity of heat toward these cold ends to reduce the temperature of the end surfaces of the bulb some 6° or 8° below the mean temperature of the cylindrical surface.

This may appear to be a rather obvious condition to be overlooked, but it is a common practice of physicists to assume that the temperature is constant over a radial cross-section near the center of a cylindrical furnace which is reasonably long in comparison with its diameter. With this in mind, the probability is even greater that a metallic conductor only 4 cm. in diameter (the end surface of the bulb), perpendicular to the axis in such a furnace, will have a uniform temperature between its center and periphery. The fact is that neither of these assumptions is justified, even in furnaces as long as twenty times the diameter. This was shown in a number of actual measurements made in different furnaces under varied conditions, differences of several tenths of a degree being found as low as 300°, and of several degrees at 1000° and higher.

This situation demonstrates the futility of depending upon metallic conductivity (of platinum) to equalize a steep temperature gradient, and again emphasizes the fact that the air-bath, or, more explicitly, the temperature distribution within the heating chamber, is the most uncertain factor remaining in gas thermometry.

On account of difficulties in manipulation and accidental leakage into the thermo-element system, we preferred not to introduce more heating coils into the furnace tube and therefore undertook to stop the loss of heat by inserting thin, platinum-covered diaframs opposite the ends of the bulb. The situation was still further safeguarded, in exchanging the platin-iridium for the platin-rhodium bulb, by adding a reentrant tube at the lower end of the bulb, to enable us to measure the actual temperature prevailing at its center as well as over the surface. We thought thus to obtain a more representative integral of the surface temperature and a competent comparison of this integral with the temperature actually prevailing at the center of the bulb.

Only one change was made in the manometric apparatus. The gas, instead of being introduced through the three-way cock at the bottom of the short arm of the manometer, which necessitated its bubbling through the mercury, was admitted by a stopcock and a slanting side tube blown into the manometer tube about 30 cm. below the fixed point.

Changes in the expansion-coefficient apparatus are described on p. 61.

12. DETAILS, ERRORS, AND CORRECTIONS.

The gas thermometer for very high temperatures has now reached a stage of development where it becomes necessary to examine many small sources of error. These will be discussed in the succeeding paragraphs without attempting to classify separately the variable errors of observation, and the systematic errors which may arise from conditions of the measurements or from constant corrections.

To bring out the plan of investigation of these errors, it will be well to recall the derivation of the gas-thermometer formula. The gas scale, as is well known, is defined by the relation

$$\frac{pv}{1+at} = K \qquad (1)$$

in which K and a are constants and t is a function of the product pv, p and v being the pressure and volume of a fixed mass of the gas. K and a are determined by two further conventions:

When $p=p_0$ and $v=v_0$ (at the melting-point of ice), $t=0$ (2)
When $p=p_{100}$ and $v=v_{100}$ (at the boiling-point of water), $t=100$ (3)

It is then evident that

$$a = \frac{p_{100}\frac{v_{100}}{v_0} - p_0}{100 p_0}$$

which defines a as the mean pressure-coefficient of the gas between $0°$ and $100°$ (when v_{100} and v_0 are nearly equal); and

$$K = p_0 v_0$$

The temperature t is therefore defined by the formula

$$t = \frac{p\frac{v}{v_0} - p_0}{a p_0} \qquad (4)$$

the scale depending upon the gas chosen, the value of p_0, and the ratio $\frac{v}{v_0}$.

In the theoretical constant-volume thermometer this ratio $\frac{v}{v_0}$ is unity, but in the experimental constant-volume thermometer it always varies considerably from 1. We have therefore preferred to treat equation (4) as the fundamental equation, introducing in place of $\frac{v}{v_0}$, however, the proper function of the expansion coefficient of the bulb material.

Since apparatus designed for high-temperature work is not suited for the most accurate determination of a, a has been treated in this discussion as a separately determined constant.

In the experimental gas thermometer there is always a small space in the tube connecting with the manometer, and this space is at various temperatures other than t. The pressure (p' or p_0') actually measured is not,

therefore, the p or p_0 of the formula. Imagine that this supplementary space is heated up to the uniform temperature t, without any change in its volume, and let the resulting corrected pressure be p (or p_0 as the case may be). Furthermore, let

V = volume of bulb at $t°$.

V_0 = volume of bulb at $0°$.

v_1 = volume of unheated space, which is at temperatures other than t (or than $0°$).

t_1 = temperature of this space.

β = linear expansion coefficient of the bulb material.

Under these conditions, formula (4) becomes:

$$t = \frac{1}{p_0 a}\left[p\frac{V+v_1}{V_0+v_1} - p_0 \right]$$

Since

$$\frac{V+v_1}{V_0+v_1} = \frac{\frac{V}{V_0}+\frac{v_1}{V}}{1+\frac{v_1}{V_0}} = \frac{1+3\beta t+\frac{v_1}{V_0}}{1+\frac{v_1}{V_0}} = 1+\frac{3\beta t}{1+\frac{v_1}{V_0}}$$

the formula for t becomes

$$t = \frac{1}{p_0 a}\left[p\left(1+\frac{3\beta t}{1+\frac{v_1}{V_0}} \right) - p_0 \right] \tag{5}$$

In this formula $\frac{v_1}{V_0}$ is a very small correction term; while the important quantities to be measured are p_0, p, a, and β. The ratio $\frac{v_1}{V_0}$ becomes of importance, however, in determining the corrected pressure p from the measured pressure p'. The derivation of this correction is as follows:

The mass of the gas in the unheated volume under the actual conditions of measurement is proportional to $\frac{p'v_1}{1+at_1}$; the mass of the gas within the bulb is proportional to $\frac{p'V}{1+at}$. If we now suppose the unheated space raised to the uniform temperature t without change of volume, the pressure being thereby raised to p, the total mass is proportional to $\frac{p(V+v_1)}{1+at}$. Therefore,

$$\frac{p'v_1}{1+at_1}+\frac{p'V}{1+at}=\frac{p(V+v_1)}{1+at}$$

whence

$$p-p' = p'\left(\frac{v_1}{V+v_1} \cdot \frac{at-at_1}{1+at_1} \right)$$

This correction is easily calculated and tabulated; or, better, the factor in parenthesis (in the second member of the equation) is plotted against temperature. In practice, the volume v_1 is divided into three portions at temperatures t_1', t_1'', and t_1''' as explained on page 58, and the correc-

tions obtained from the curve for each of these portions are simply added together to obtain the total correction $p - p'$. With these corrected pressures, p_0 and p, the temperature t is calculated by formula (5) on page 53.

This method of computation yields, of course, the same values for t as the formula on page 40, but has the advantage of showing more clearly the magnitude of the corrections.

The discussion of errors and corrections will now be taken up under the general outline sketched on page 49.

TEMPERATURE OF THE GAS IN THE BULB.

Uniformity.—Above the temperatures where a liquid or vapor bath can be used to secure uniformity, the differences of temperature between different parts of a furnace have always been a serious limitation to the accuracy of the gas thermometer. This variation, even in a furnace containing well-conducting materials, is much larger than has usually been assumed, and the three equalizing factors of conductivity, radiation, and convection by air-currents are all credited with much greater influence in bringing about uniformity than they really possess. It sometimes happens that our faith in these factors is inversely proportional to our quantitative information about them.

In the first measurements with the new bulb, the end elements were placed on the axis of the bulb, in positions 1 and 9 (Fig. 8), instead of on the periphery of the cylinder. It became evident at once that the supporting tube in the bottom of the furnace, used in earlier measurements, had a considerable cooling influence on the central portion of the bottom, an effect which would tend to make the results low. This effect was largely obviated by replacing the heavy magnesite tube (Fig. 1, p. 18) with a thin Marquardt porcelain tube, in the top of which was placed a Marquardt crucible, cut out into a three-pronged support (Fig. 9, p. 56). The bottom of the crucible acted as a screen to prevent radiation from the bottom of the bulb, and the smaller thickness and thermal conductivity of the tube practically prevented the loss of heat from the bottom by conduction. Later, a second diafram was added about 1 cm. lower down, primarily for the purpose of centering the tube and bulb in the furnace, but without noticeable effect on the temperature distribution.

In addition to the three thermo-elements mentioned, a fourth was located inside the reentrant, in position 8.[1] Several trials under varied conditions confirmed the fact that this element, when the other three were set equal, was 2° to 3° hotter than the one on the outside. A thorough exploration of the distribution of temperature over the surface of the bulb was therefore undertaken.

Since the number of wires which could be led out through the packed joints was limited, the plan was adopted of using the bulb itself as a differential thermo-element, single platinum wires being tied to the bulb at points whose temperature was to be determined. Each of these wires formed, with the platinum of the standard element tied to the bulb at the middle, a differential element which would read zero if the wires were alike and if no difference of temperature existed between the two points on the bulb.

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[1] See Fig. 8, and note, p. 55.
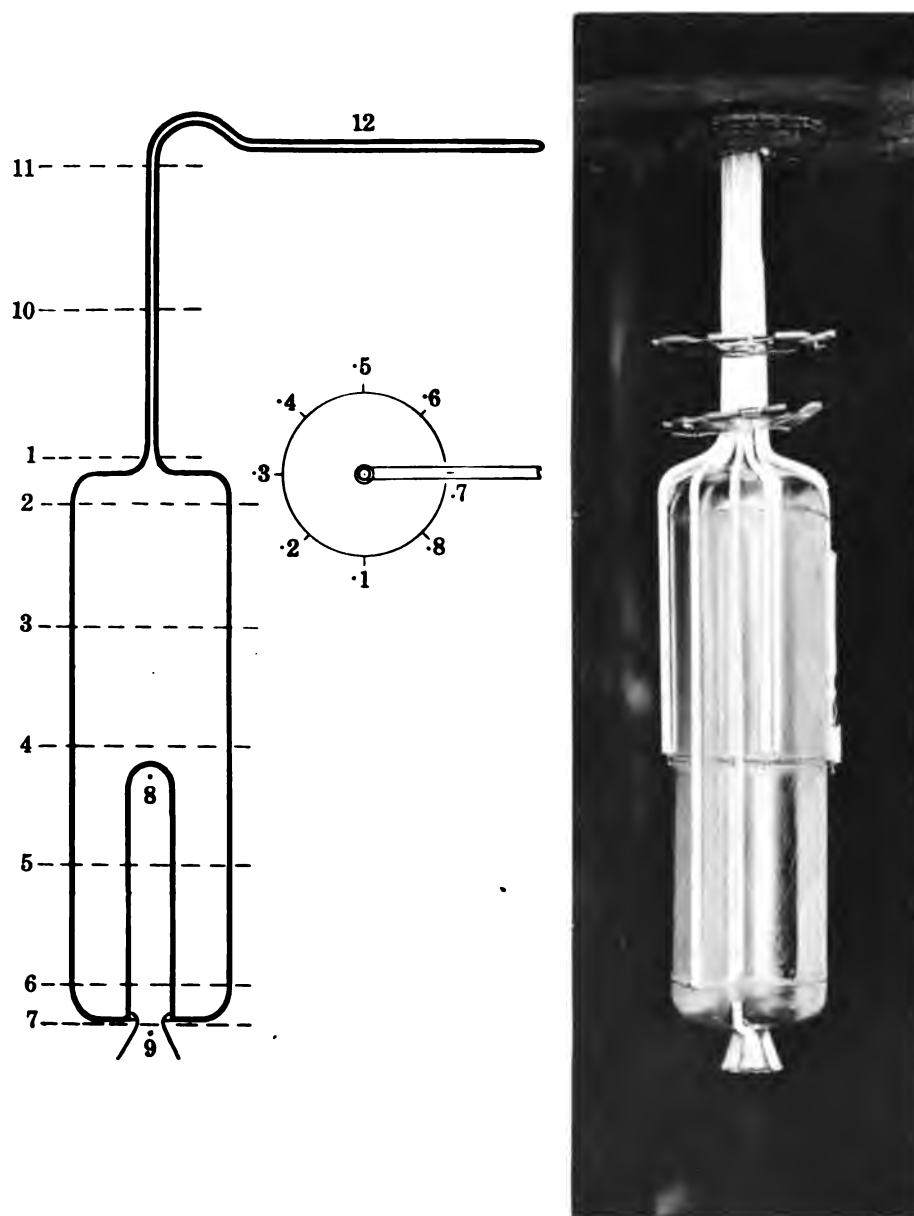
FIG. 8. Vertical section of the gas thermometer bulb, and photograph made after the palladium-point determination showing all the elements and the diaframs in position. The numbers are used in the tables of data to designate the positions of the thermo-elements grouped about the bulb.

The relation of the wires was established by sealing each in turn to the platinum of the standard, and measuring their E. M. F. at various temperatures. The readings varied, according to the quality of the wire, from 0 to 40 microvolts. The method of evaluating differences of temperature, when such existed, is discussed on page 66.

The distribution of temperature lengthwise of the bulb was first investigated, and auxiliary wires were placed at the levels 1 (base of stem), 2 (top shoulder), 6 (bottom shoulder), 7 (bottom, outside of funnel), in addition to thermo-elements at 4 (middle outside), 8 (inside reentrant), and 9 (bottom, just inside of funnel).[1]

With this system of thermo-elements, it was found that at 1082°, when 9 was brought to equality with 4 and 1, then at the bottom of the bulb element 6 was superheated 6° to 8° and element 7 about 4°, due entirely to the fact that the thermo-element at 9, not being in contact with the bulb, lost sufficient heat by conduction and radiation downward to keep its temperature below that of the metal surrounding it. The element 8, on the other hand, received heat by conduction up the reentrant tube and by radiation from below, which made it read higher than the element at the same level outside. The element at position 9 was therefore discarded and each setting of temperature was made with the elements which were attached directly to the bulb, i. e., by bringing 1, 4, and 7, or 2, 4, and 6 to uniform temperature. In fact, at the highest temperatures where the danger of unequal distribution was greatest, both arrangements were employed in successive measurements at each temperature.

The temperature between the middle and the top shoulder was also examined in several experiments. The temperature at this position was found to be within 0.5° of the other two, with a tendency to be lower than these.

Further experiments showed that, in addition to the possibility of vertical variation of temperature, there was a variation around the circumference of the bulb. This amounted in the worst case (at 1450°) to a variation of 1.3° from the mean, four elements being used around the circumference to make the test. This variation seemed to be due either to unequal conductivity of the furnace material at different points or to the flaking off of small portions of the furnace lining, leaving exposed places on the wire. Variations of this character are probably an unavoidable result of using a furnace where the heat supply is so near to the point where it is measured, as is the case with the furnace coil which is wound on the inside of the tube. This form of winding is necessary, however, in order to reach the highest temperatures, so that absolute uniformity of temperature around the bulb was sacrificed to the increased range of the instrument.

After this variation was discovered, measurements were always made with four elements at equal distances around the circumference of the bulb and the mean of their readings was taken.

In order to be perfectly certain that no systematic error was being introduced by using this one form of furnace (Fig. 9) throughout, it was replaced

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[1] The system of numbering the positions of elements on the bulb is shown in Fig. 8. The figure before the decimal point indicates the horizontal level, the figure after the decimal indicates the orientation around the bulb. For instance, an element in position 3.5 would be about half-way between the top and middle and on the side of the bulb away from the front of the apparatus.

temporarily by a furnace of platinum wire wound on the *outside* of a similar tube. In this way a heavy mass of good heat-conducting material was introduced between the source of heat and the bulb, with the expectation that a more uniform temperature might thereby be obtained in the inside space. The two types of furnace are shown in Figs. 9 and 10.

A measurement at the copper point with the outside-wound furnace gave as the melting-point of copper 1082.6°, a value identical with the mean of the results obtained with the other furnace, thus proving that no systematic error need be feared from the inside-wound type of furnace. The horizontal uniformity obtained in the outside-wound furnace was better than that in

<center>FIG. 9.   FIG. 10.</center>
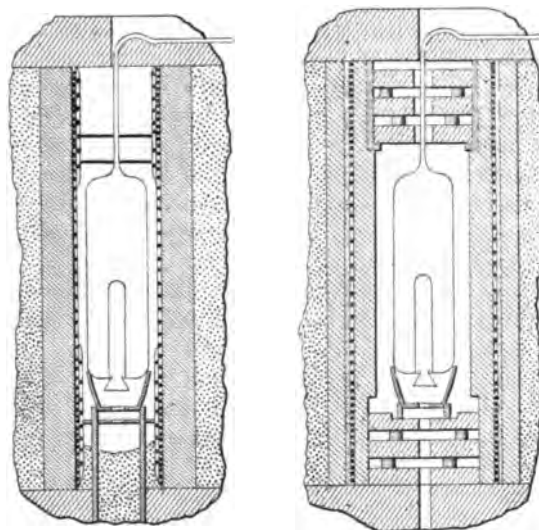
FIG. 9. Section of furnace and bulb showing an arrangement of coils and diaframs about the bulb which gave a most uniform temperature distribution in the measurement of both high and low temperatures. The supplementary end coils were independently heated and regulated.

FIG. 10. A special arrangement of the heating coil and diaframs designed to give a very uniform temperature distribution about the bulb. The coil was heavily ballasted inward with a good heat conductor and outward with a poor conductor. The heating coil was also divided into three sections which could be independently regulated. This furnace was used at the copper point only.

the inside-wound, but the furnace was more difficult to regulate and to hold at a given temperature.

Constancy of conditions.—Several causes interfered with the establishment of a constant temperature for observation. The three heating currents required constant observation and readjustment with the gradual extension of the heated zone toward the outside of the furnace. This came to equilibrium for a particular temperature after about half an hour, after which the bulb was held steady 15 to 30 minutes longer before readings of the pressure were taken. The temperature thus established could be relied upon to remain constant to within 1 to 3 microvolts (0.1° to 0.3°) during the course of the pressure measurements.

Above 1100° a noticeable leakage of current from the heating coil into the bulb and thermo-elements frequently appeared. This may have been

due in part to conductivity across the narrow air-space between bulb and coil, but was probably chiefly due to accidental contact between the protecting tube of one of the thermo-elements and the furnace wall. To obviate any uncertainty from this cause, it was found necessary to use alternating current for all temperatures above 1100°. This was less easy to regulate than the direct current from storage batteries, but by careful regulation of the voltage of the motor generator supplying the alternating current, equally satisfactory results were obtained.

The constancy and exactness of the temperature at 0° were beyond question. On several occasions pressure measurements at 0° were made at intervals of 30 to 60 minutes and no measurable difference was found. Similarly, repacking the bulb in a fresh supply of ice gave exactly the same value.

DEFINITION OF TEMPERATURE BY MEASUREMENT OF PRESSURE.

The procedure in measuring the pressure, p', was as follows: First the three mercury thermometers on the manometer were read to determine the temperature of the mercury column and scale; then three to four settings of the barometer were made, alternating with measurements of the manometer. The mercury thermometers were read again at the close. During this interval the other observer made as many readings as possible of all the thermo-elements.

Before the manometer was connected to the bulb, the point on the scale corresponding to the reference point of the manometer[1] was determined once for all before the manometer was connected to the bulb, by connecting the two arms and raising the mercury to the point, as in a regular pressure measurement. Subsequent manometer readings were subtracted from this fixed level, and the resulting difference corrected for the temperature and calibration corrections of the scale and then reduced to 0°. The barometer reading was similarly corrected. The algebraic sum of the two gave the pressure p', in terms of a centimeter of mercury at 0° and at the latitude and elevation of the laboratory. Since the absolute value of the pressure does not enter into the gas-thermometer formula, corrections for altitude and latitude are superfluous.

Errors and Corrections in p'.—The level of the fixed reference-point of the manometer varies with the temperature of the room because of the difference in expansion of the brass scale on the one hand and of the glass tube of the manometer which carries the fixed point on the other. This correction can be calculated from the expansion coefficients of the materials and amounts to 0.04 mm. per 5°. Its direction and amount were checked experimentally by determining the fixed point at two temperatures differing by about 10°, the room being open on a cold day for the one case, and closed and heated for the other. The difference found was 0.09 mm., and that calculated 0.08 mm.

The lengths of the divisions of the brass scale were corrected for change of temperature by a formula determined for this scale at the Normal Aichungs-Kommission, the absolute length of the scale having been determined at 16°. In addition, calibration corrections, determined for each

[1] Pages 19 and 27.

millimeter of the scale, were applied. The total scale correction was always less than 0.15 mm., hence the temperature measurement by the adjacent mercury thermometers was abundantly accurate for this purpose.

The length of the mercury column was reduced to 0° by the expansion coefficient given in the Landolt-Börnstein-Meyerhoffer Tabellen. This correction varied from 0 to about 3.00 mm. As the mercury thermometers were calibrated and read to 0.1° the uncertainty in this correction due to uncertainty in the room temperature may amount to 0.05 mm. For their calibration the mercury thermometers were compared with a Richter standard thermometer calibrated at the Reichsanstalt.

The barometer reading was corrected to 0° by the Landolt-Börnstein-Meyerhoffer table for barometer with brass scale. Two Fuess barometers were used. Both had been tested by the Bureau of Standards; one had an absolute correction of 0.06 mm., the other was exact. This was checked by direct comparison of the two. The variable error in the barometer is probably about the same as in the manometer reading (0.05 mm.). On a very windy day, or during the approach of a storm, the barometer was too unsteady to permit satisfactory measurements to be made.

A further small correction to the barometer was necessary to allow for the weight of the air column between the cup of the barometer and the top of the mercury in the open manometer column. This correction was appreciable, amounting to 0.16 mm. in the extreme case.

To give some idea of the effect of these small corrections upon the final temperature measurement, it may be added that 1.00 mm. corresponds approximately to 1°.

To determine the corrected pressure, p, from the measured pressure, p', (see page 53), the volume of the unheated space, v_1, connecting the bulb with the manometer, must be known.[1]

<center>TABLE VII.—UNHEATED SPACE.</center>

Space.	Volume before Apr., 1909.	Volume after Apr., 1909	Uncer-tainty of volume.	Uncer-tainty of tempera-ture.	Maximum effect, at copper point, of the errors.
	cc.	*cc.*		°	°
Pt-Rh capillary,bulb to top furnace(v_1')	0.055	0.055	0.002	100	0.04
Pt-Rh capillary, top to outside furnace (v_1'')	0.086	0.086	0.003	50	0.20
Pt-Rh capillary to gold capillary	0.102	0.054			
Gold capillary	0.094	0.066	0.015	0.5	0.20
Pt capillary and Ni valve	0.025	0.025			
Space above meniscus	0.023	0.023			
Total	0.385	0.309			0.45

Note: rows "Pt-Rh capillary to gold capillary", "Gold capillary", "Pt capillary and Ni valve", "Space above meniscus" are braced together as v_1'''.

This was recalculated because the dimensions of the capillary of the second bulb were somewhat larger than those of the first. The figures are given in Table VII. This volume was reduced in April, 1909, by bringing the manometer closer to the furnace, since the water-jacket of the furnace cut off the heat so completely that there was no risk in bringing

the manometer as close as possible (35 cm). The volume v_1 was thereby reduced from 0.39 cc. to 0.31 cc., and the ratio $\dfrac{v_1}{V_0}$ from 0.00187 to 0.00150.

The volume V_0, which enters into the correction term (see page 53) was determined by weighing the bulb empty, and filled with distilled water at a known temperature. A very accurate determination of this volume was not necessary, the important requirement being that the volume should not change during a run. A check on change of volume was obtained in the measurement of the value of p_0. The volume of the bulb at 0°, up to the base of the capillary stem, was found to be:

	c.c.
On 13 June, 1908 (new)	205.74
On 18 June, 1908 (after 1450°)	205.75
On 20 April, 1909	205.82

The volume of the unheated space, v_1, was arbitrarily divided into three portions for the convenient determination of its average temperature, t_1. The first portion, v_1, extended from the base of the stem to the top of the upper brick of the furnace (see Fig. 1); the second portion, v_1'', included the capillary stem as far as the outside of the furnace; the third portion, v_1''', extended to the surface of the mercury in the manometer and included all of that portion of the unheated space which remained at room temperature.

The temperatures of the portions v_1' and v_1'' were determined by placing a thermo-element at different points along the stem during several of the runs. As this temperature does not need to be known accurately, a few measurements gave a sufficient indication of the distribution of temperature in the portion of the "unheated space" within the furnace.

A liberal estimate of the degree of uncertainty in the values of v_1 and t_1 has been made and is included in Table VII, together with the effect which such errors would have on the calculated temperature, t, at the copper point.

Errors and Corrections in p_0'.—The same instrumental corrections apply to p_0' as to p'; but their proportional magnitude is, of course, larger. The values of the uncertainty in t due to these small errors will be found in Table X, p. 69.

As appears in Table X, the largest possibility of error in p_0 comes from corrections for the temperature of the mercury columns. These errors always affect p_0 and p in nearly equal magnitude and become negligible in their effect upon $p - p_0$, but appear (uncompensated) in p_0 in the denominator. See equation (5) p. 53. To insure the constancy and accuracy of the temperature of the mercury column, the manometer was jacketed over its entire length with a pasteboard jacket. This was sealed tight at the permanent joints, and built up in removable sections over the portion of the manometer through which the height of mercury varied. A current of air was circulated through this jacket by a large-capacity suction jet. At the same time an electric fan kept a rapid upward current of air flowing over the entire apparatus. The temperature of the room was also kept as nearly constant as possible. Under these conditions the measurement of p_0' was reproducible within 0.02 to 0.03 mm., corresponding to about 0.2° at 1500°. This was checked experimentally on several occasions by

making readings of p_0' under different conditions of room temperature and barometric pressure.

Changes in the value of p_0 (the ice-point) after heating to high temperatures have always been disturbing factors in gas-thermometer measurements and have introduced uncertainties of a very intangible kind. This was especially true of the porcelain bulbs formerly used, where both changes of volume and emission or absorption of gases by the walls occurred. The restoration of the platinum metals to favor as materials for the gas-thermometer bulb has practically eliminated this uncertainty. During the present work small changes in the value of p_0 have frequently occurred after heating to a high temperature, which seem not to be due to any change in volume, for the determinations of the volume, V_0, given above (p. 59), show a total change after a year's work corresponding to less than 0.1 mm. in p_0. In the early part of the work, the passage through the bulb wall of hydrogen or some other gas produced by the reducing action of wood fiber in an asbestos board insulator within the furnace, was suspected as being the cause of irregularity, particularly in view of the fact that Holborn and Valentiner had difficulties from this cause.

Further, it was several times observed that heating the furnace and bulb to a higher temperature than they had reached before caused a slight increase in the value of p_0—whether due to some gas passing in from the outside or coming out of the wall of the bulb is not known. Air dried over calcium chloride was used outside of the bulb in the furnace inclosure throughout the work, and no indication was ever obtained of the passage of either oxygen or nitrogen through the wall of the bulb, since measurements at a given temperature (after the first heating to that temperature) gave the same value of p_0 within the error of measurement.

On one occasion an almost inappreciable leak in the manometer connection caused some uncertainty. All measurements affected by this error, when it was discovered, were rejected.

THE GAS.

Since the gas-thermometer apparatus as arranged for high-temperature measurements is not suited to a determination of the value of a (the pressure coefficient of the gas from $0°$ to $100°$) with an accuracy comparable to that attained by Chappuis,[1] the value of a was treated as a constant. The figures used were:

$$\text{For } p_0 = 345 - 347 \text{ mm., } a = 3665.8 \times 10^{-6}$$
$$\text{For } p_0 = 217 - 221 \text{ mm., } a = 3664.0 \times 10^{-6}$$

It will be recalled that a number of independent determinations of a for different pressures were made (p. 40) with the platin-iridium bulb, but they show no appreciable difference from those by Chappuis within the experimental error of the apparatus. The probable error in Chappuis's results is not great enough to affect the high-temperature values.

Pure nitrogen was used throughout as the thermometric gas.[2] The

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[1] Trav. Mem. Bur. Int., 6 and 12, 1888 and 1902.

[2] It was prepared by dropping a solution of 200 grams of sodium nitrite dissolved in 250 grams of water into a warm solution containing 350 grams of ammonium sulphate and 200 of potassium chromate in 600 of water. It was passed through a mixture of potassium bichromate and sulphuric acid and stored over water. For use in the gas thermometer it was purified by passing through calcium chloride, hot copper gauze, potassium bichromate in sulphuric acid, 2 bottles potassium pyrogallate solution, sulphuric acid, calcium chloride, and phosphorus pentoxide.

storage tank was refilled several times so that not all the gas was from the same original supply; the filling of the bulb was also changed several times. The bulb was first completely evacuated and heated to a high temperature, after which the connections and bulb were rinsed out several times with the purified gas before the final filling. .

EXPANSION COEFFICIENT OF THE BULB (β).

The substitution of a new alloy in place of the platin-iridium made necessary a new determination of the expansion coefficient of the bulb material. The method of its determination and the comparator used for the purpose have been fully described in the earlier pages of this paper (p. 27) and do not require to be repeated here.

Three additional precautions were taken in carrying out the measurements. The bar was increased in length to 500 mm. and in diameter to 6 mm., in order to increase the sensitiveness of the determination and the uniformity of temperature along the bar respectively. In this case the bar was also made at the same time and from the same alloy as the bulb itself, and was therefore identical with it in composition.[1]

In ruling the bar, the lines were spaced 0.2 mm. apart instead of 0.5 mm., as in the previous investigation. This enabled a greater number of observations to be made within a narrow region than before, and thus made it possible to avoid the error from parallax described on page 34.

The third precaution involved a slight change in the comparator itself, and was made at the suggestion of Chappuis. Our custom had been to verify the distance between the fixed hairs of the microscopes before and after each heating by measuring this distance in terms of a standard brass bar calibrated at the Bureau of Standards. The brass bar was then replaced by the platin-iridium bar before the heating began, and the length of the latter was measured in terms of the initial distance between the fixed hairs, at intervals of 50° or 100° up to 1000°. This mode of procedure involved the assumption that the agreement of the measurements made before and after heating afforded adequate proof that no change had taken place *during* heating. The justification for this assumption lay in the facts that—

(1) The furnace was completely water-jacketed to prevent any heat reaching the microscopes from the furnace. .

(2) Suitable insulating material introduced between the observer and the microscopes cut off any disturbing influence from the near approach of the observer's body.

(3) The microscopes themselves, and the carriages upon which they were mounted, were connected by carefully selected invar bars of negligible expansion coefficient.

(4) The faithful agreement of all the measurements on the standard brass bar before and after the many heatings left no reason for suspecting such a variation in the cross-hair distance.

Notwithstanding these conditions, it appeared to Chappuis that some positive proof should be offered that the distance between the cross-hairs remained unchanged while the heating was going on, inasmuch as all the measurements were made in terms of this distance. Accordingly, at his

[1] The new bulb, as well as the bar, were made with the utmost care by Dr. Heraeus, of Hanau, Germany, for this investigation.

suggestion, it was arranged to retain a standard unheated bar in the field of the microscopes throughout the readings, so that the distance between the cross-hairs would be subject to check at any time during the observations. The arrangement made for the purpose is very simple and effective, as can be seen from the neighboring diagram (Fig. 11). The last two series of measurements were made with this appliance, and the fixed distance was found to remain constant throughout the series to within 0.003 mm., although on first setting up the apparatus a gradual adjustment of strain, amounting to 0.012 mm., took place during the first two days.
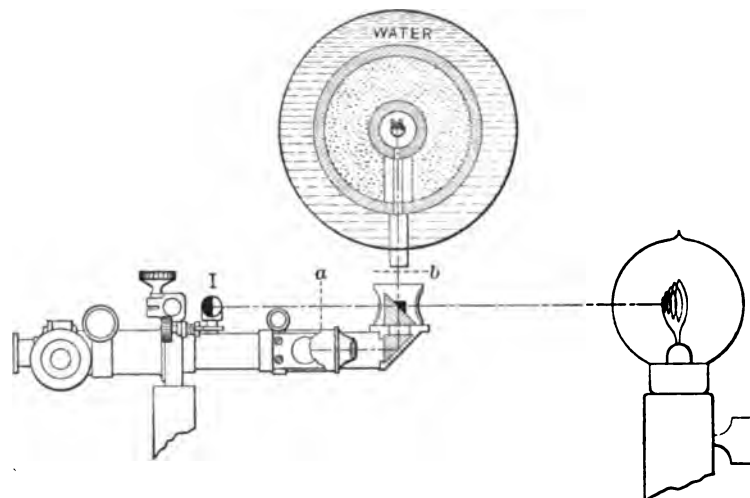
Fig. 11. A transverse section of the expansion-coefficient furnace at one of the openings, showing the method of illumination of the heated bar and the standard cold bar (I) together with an arrangement for checking the distance apart of the cross-hairs at each temperature. With a screen inserted at a, only the hot bar is visible; with the screen at b, only the cold bar. Compare with Fig. 6, p. 29.

The determination of β is subject to two errors: The first is uncertainty of temperature, the second occurs in the measurement of the change in length. It was impossible to wind the furnace (70 cm. long and 1.5 cm. inside diameter, with two side openings) so as to give a perfectly uniform temperature along the bar; but as the furnace winding and consequent distribution of temperature were varied considerably for each run, the uncertainty from this cause was eliminated in the average of all the observations. The error in the temperature measurement itself was probably not over 2°, which would give an error of less than 0.2 per cent at the highest temperature. Two thermo-elements with a common junction were used, one entering from each end of the furnace. This not only gave a second temperature reading in confirmation of the first, but a positive check upon the appearance of contamination in the thermo-elements.[1]

With a half-meter bar and a temperature interval extending from zero to 1400°, the total expansion amounts to about 7.8 mm. The micrometers reading the expansion were read with an accuracy of 0.002 mm.

There was again some indication of a small hysteresis in the expansion and contraction. Although the amount was not much greater than the

[1] See p. 23.

experimental error, the measurements indicate that the bar was slightly shorter after each heating than before, and that it gradually regained its original length. (See also p. 35.)

The measurements at room temperature are given in Table VIII. The five measurements in this table which were made within a few hours after the bar had cooled from a high temperature, excluding the two where the

TABLE VIII.—LENGTH OF PLATINUM-RHODIUM BAR.

Date.	Maximum preceding temperature	Length at o°.	Date.	Maximum preceding temperature.	Length at o°.
1 July 1908	(New)	500.068	26 Sept. 1908	1150°	500.094
6 July 1908	900°	500.110[1]	1 Oct. 1908	25	500.119
9 July 1908	28	500.105	6 Oct. 1908	1300	500.034[2]
13 July 1908	900	500.098[1]	27 Oct. 1908	900	500.108[1]
17 Sept. 1908	900	500.108[1]	30 Oct. 1908	1400	500.096
19 Sept. 1908	1200	500.090	6 Oct. 1909	28	500.103
20 Sept. 1908	23	500.105	12 Oct. 1909	22	500.108[1]
22 Sept. 1908	1200	500.087	13 Oct. 1909	1000	500.109
24 Sept. 1908	24	500.096	15 Oct. 1909	1400	500.074[2]

bar was bent, average 500.095; while the ten measurements (excluding the first) which were made two days or more after heating average 500.106. The difference is only 0.002 per cent of the total length, or 0.12 per cent of the total expansion to 1500°, or about 0.7 per cent of the expansion to 300°. This effect is, therefore, probably responsible for the observed irregularities between 0° and 300°, at which point most of the temperature measurements were begun.[3]

THE THERMO-ELECTRIC MEASUREMENTS.

The electromotive forces of the elements attached to the bulb were measured with a Wolff potentiometer. The standard of electromotive force used was the international volt, in terms of which the E. M. F. of the Clark cell is 1.4328 at 15°, and of the saturated cadmium cell used is 1.01835 volts at 25°.

Several small corrections are necessary in order to obtain the true E. M. F. of the thermo-element. The calibration corrections of the potentiometer (Reichsanstalt calibration) were all negligible except that for the fixed resistance to which the standard cell was attached. This correction amounted to 1.3 microvolts in 10,000. The correction for the change of resistance with temperature of the potentiometer was also negligible. The E. M. F. of the standard cell varies with the temperature; hence, the temperature of the cell was read at each measurement and a small correction applied. The readings were correct at 21.5°. For a variation of 5° from this temperature the correction was 2.2 microvolts in 10,000 microvolts. The resistance of the contacts of the potentiometer, and the small E. M. F.'s existing at contact points in the circuit of the thermo-element, introduced

[1] After interval of 4 to 7 days.
[2] After heating beyond the last temperature at which measurements were made it was discovered that the bar had become bent by sagging under its own weight.
[3] Kammerlingh-Onnes (Konink. Ak. Wet. Amsterdam, Proc., 10, 342, 1907) has found the same effect after cooling platinum to very low temperatures.

another small error which was determined by placing the thermo-element in ice and reading the E. M. F. This correction varied for the different elements from −1 to +4 microvolts.

As a check upon the absolute value, a Weston standard cadmium cell (calibration by the Bureau of Standards) whose E. M. F. was read directly on the potentiometer, was compared with the saturated cell each day. The agreement of the corrected values was usually within 0.5 microvolt. As in the case of the pressure measurement, the absolute value of the E. M. F. is not of importance, since it is used only for transference from the fixed points to the gas thermometer; the above corrections were applied, however, to reduce the readings to a common standard.

The effect of contamination (p. 23) of the thermo-element wires in furnace readings was much greater than the above-mentioned errors.[1] Up to 1100° the contamination was not serious, but above that temperature the wires take up iridium together with some rhodium. It was hoped that the replacement of iridium in the bulb by rhodium, which is much less volatile, would do away with this error, but there appeared still to be a very small percentage of iridium or other contaminating substance in the furnace or in the furnace wire, enough to affect the thermo-element wires appreciably, even though this furnace wire had been especially purified for this purpose.

Although the task became much longer and more laborious, it was thought wise to avoid the error from contamination, even of this diminished magnitude, rather than to attempt to compromise with it by any scheme of approximate evaluation. Accordingly, after every exposure of sufficient length to endanger the thermo-electric readings, all the thermo-elements were removed from the furnace and their wires tested for homogeneity. Where contamination was found, the contaminated portion of the wire was at once cut off. This is the only absolutely safe method of avoiding errors from this cause, for it amounts to the use of new thermo-elements exclusively in all the determinations of temperature distribution within the furnace as well as for establishing the absolute temperature of the metal melting-points.

Testing the Thermo-element Wires.—A very simple method of testing the wires for contamination has been developed, which consists in connecting the junction end of the wire to be tested, together with an uncontaminated wire, to the potentiometer and moving the free end of the standard wire along the wire to be tested, while heating the contact point of the two with a blast lamp.[2] The variation of the E. M. F. produced at this junction indicates the degree of contamination of the wire; in the uncontaminated portion this E. M. F. is small and constant within 3 microvolts. The temperature obtained by the blast-lamp flame is sufficiently constant for the purpose and lies between 1460° and 1500°.

The wires could be relied upon to give a constant E. M. F. within 3 microvolts at 1000° over a length of at least 50 cm, so that redeterminations of the fixed points were not necessary after cutting off each small portion of contaminated wire. Each test for contamination was continued over the 50 cm. of wire adjacent to the hot junction and so served as a test for the

[1] For a more thorough discussion of this effect, see W. P. White, Phys. Rev., 23, 449-474, 1906.
[2] W. P. White, loc. cit., p. 454.

homogeneity of the new wire which replaced the portion cut off.   In two
cases a sudden change of E. M. F. along the unused wire amounting to
about 10 microvolts showed the probable presence of a junction point in
the original sample from which the wire was drawn.   Such a junction point
was of course not introduced into the heated portion of the furnace.

In this connection, it should be pointed out that the relative weight to
be given to the element inside the bulb, as compared with the outside
elements, is greater at temperatures above 1100° than at temperatures
below, for two reasons:

(1) The temperature at the middle of the bulb is not so much influenced
above 1100° by the temperature of the lower part of the furnace as it is
below 1100°.

(2) The outside elements are much more subject to contamination than
the inside element by reason of the protection afforded the inside element
by the intervening bulb walls against contaminating material from the
heating coils or the furnace.

This is well shown by the data in Table XV, p. 105, on the melting-points
of diopside, nickel, and cobalt.   In the first measurements of these temper-
atures, the elements were left on the bulb through several runs, in con-
sequence of which the readings of the outside elements on the bulb steadily
decreased, whereas the temperatures derived from the inside elements are
fairly constant.   The contamination of the inside element was found to be
less in amount and distributed over a region of more constant temperature.

For insulating the thermo-element wires from the bulb and furnace,
capillary tubes, both of Marquardt porcelain and of silica glass, were
employed.   The Marquardt tubes are open to the objection that they are
very porous and offer little protection against contamination.   The silica
glass capillaries protected the wires very much better, but at 1100° and
above they devitrified rapidly and at the end of a measurement at 1400°
or over fell from the wires in small fragments, so that the wires had to be
taken off and reinsulated after a single run.

For the convenience of others who may confront similar problems, it
may be added that such extreme precautions as cutting off the elements
at the first sign of contamination are excessive for most purposes.   The
region of highest temperature, and therefore of most rapid contamination
in a good furnace, is also a region of constant temperature.   Contamina-
tion would therefore produce little effect upon the reading of the thermo-
element until it had crept out into the colder parts of the furnace, which
it will do slowly during long exposures.   The distribution of the contami-
nation in an aggravated case is shown in the table on page 66, which is
arranged in such a way that not only the magnitude of the contamination
but also its distribution with respect to the bulb is roughly shown.   The
electromotive forces are determined, as has been explained, by bringing
successive points of the contaminated wire into contact with an uncon-
taminated one in a blast flame (temperature, 1460°–1500°), the cold junction
being maintained constant at 0°.   The absolute magnitude of the numbers
in the column "before exposure" represents the electromotive force between
two uncontaminated platinum wires of (nominally) equal purity.   Its
constant value is a measure of the homogeneity of the new wire.   Its

departure from this constant value "after exposure" is a measure of the contamination it has received. Slight irregularities are the result of variations in the blast-flame temperature. Such observations merely serve to furnish information about the distribution and approximate amount of contamination received by the element, but do not of themselves provide the data to correct its reading in a particular case.

It was found desirable to glow the thermo-elements occasionally by sending through them a current of from 12 to 17 amperes, depending upon the size of the wire. The glowing served to clean, soften, and straighten the wires, but did not affect the permanent electro-motive force of the element if not too long continued. The electro-motive force of a new element, however, was found to change on heating by as much as 10 micro-volts in 10,000. Elements made from freshly drawn wire were therefore always glowed for 5 minutes before they were calibrated and used.

	Centi-meters from hot junction.	Before expos-ure (micro-volts).	After exposure (micro-volts).
	40	−4	− 4
	35	−6	− 8
Outside of furnace......	30	−8	− 7
	25	−9	− 6
Bend of stem...........	20	−6	−10
	15	−5	− 3
	12	−5	+ 2
	10	−5	+ 9
Shoulder of bulb.......	8	−5	+83
	6	−5	+83
	4	−6	+41
	2	−6	+55
Middle of bulb.........	0	−8	....

Integration of Temperatures over the Bulb.—By the method which has been already described (p. 54), the differences of temperature between the ends of the bulb and the middle were determined differentially by means of platinum wires attached to the bulb itself. Temperatures about the circumference were measured by separate thermo-elements, as it was not practicable to measure these differences differentially because of the necessity of passing a platinum binding wire around the bulb to hold the four elements in position. A check on the accuracy of this differential method was obtained by using in one case a thermo-element at the top shoulder of the bulb and thus measuring the temperature at this point both directly and differentially by means of the platinum wire of this element. The two temperatures agreed within $0.8°$ when the deviation from the middle was $6°$; when the temperatures at the middle and top were nearly equal, the two methods agreed to $0.1°$.

Table IX contains approximate values of $\dfrac{\Delta e}{\Delta t}$, the rate of change of E. M. F. with temperature, at various temperatures from $400°$ to $1500°$, both for the 10 per cent rhodium alloy and for the 20 per cent alloy of which the bulb was made. The data for the 20 per cent alloy (which need be only approximate) were obtained by two methods:

(1) An element was made up by combining a platinum wire with the 20 per cent rhodium bar used for the expansion coefficient determination, and its readings were compared directly with those of a 10 per cent rhodium element in the melting-point furnace.

(2) A platinum wire was connected from the stem of the gas-thermometer bulb outside of the furnace to the ice box, and the E. M. F. determined against the standard platinum wire attached to the middle of the bulb. In both cases the E. M. F. of the junction of platinum with the rhodium alloy at room temperature was applied as a correction.

TABLE IX.—VALUES OF $\frac{\Delta e}{\Delta t}$ FOR THE ALLOYS 90 PT 10 RH AND 80 PT 20 RH.

Temperature.	90 Pt 10 Rh (microvolts per 1°).	80 Pt 20 Rh (microvolts per 1°)
°		
400	9.5	11.5
600	10.2	12.8
800	10.8	14.2
1000	11.5	15.6
1200	11.9	16.9
1400	12.1	17.5
1500	12.1	17.8

In order to obtain the true E. M. F. corresponding to the temperature as measured by the pressure of the gas in the bulb, it is necessary to integrate the various readings over the surface of the bulb. The following arbitrary weights were given to the different positions of elements on the surface:

Top axis (position 1)............................. 5
Top shoulder (position 2)......................... 20
Middle (4 elements) (position 4).................. 55
Bottom shoulder (position 6)...................... 15
Bottom axis (position 7).......................... 5

The elements on the axis at both top and bottom, although sometimes deviating from the others, have comparatively small weight, as they affect only a small portion of the total volume. The element at the lower shoulder of the bulb is given less weight than that at the top because of the smaller volume of the lower half, due to the presence of the reentrant tube.

It was easy to show experimentally that it matters very little what these relative weights assigned to the different readings may be, since the total correction was always small. In a number of cases, two different settings of the temperature distribution were made at each temperature, one in which the elements at the top and bottom shoulders of the bulb were made equal to the middle, and one in which the elements at top and bottom on the axis of the cylinder were made equal to the middle. The pressures corresponding to these two settings, reduced to the same reading of the standard element, are shown for several typical cases in the table below.

Date.	Temperature.	Pressure when 1, 4 and 7 were equal.	Pressure when 2, 4 and 6 were equal.
	°	mm.	mm.
22 January, 1909......	1082	1038.82	1038.64
2 July, 1909.........	1395	1285.43	1285.17
17 September, 1909...	1489	1331.40	1330.63
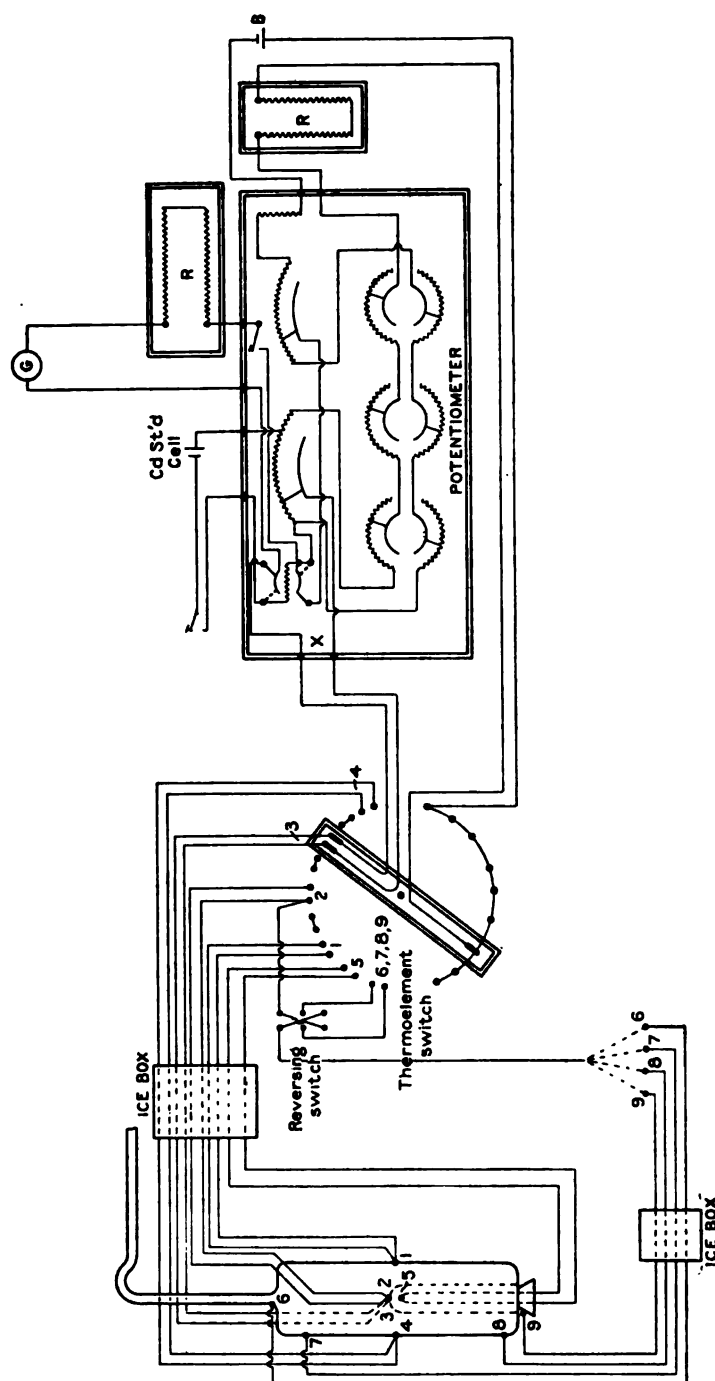
FIG. 12.   Diagram of thermo-element connections from the gas-thermometer bulb to the potentiometer.

It is evident that even without any correction for the different distribution in the two cases, the readings agreed within 0.2 to 0.8 mm. or about 0.2 to 0.9°, so that the variation between any two arbitrary sets of weights which might be given to the different readings must lie well within this limit.

The thermo-element connections, from the gas-thermometer bulb to the potentiometer, are shown diagrammatically in Fig. 12.

SUMMARY OF THE ERRORS.

The effect on the final temperature of all the errors and corrections which have been discussed in this section is shown in summarized form in Table X. The figures of this table serve to emphasize the statements already

TABLE X.—ESTIMATED ERRORS AND THEIR EFFECT ON THE VALUE OF t.

Quantity affected.	Source of error.	Amount of error.		Effect on t.	
		At 400°.	At 1500°.	At 400°.	At 1500°.
(A) Temperature of gas.	Temperature differences over bulb surface.....	2 mv.	5 mv.	$\pm 0.2°$	$\pm 0.4°$
	Variability............	0	1 mv.	0	$\pm 0.1°$
(B) p_0.........	Reference point........	0.02 mm.	0.02 mm.	$\pm 0.04°$	$\pm 0.15°$
p_0.........	Manometer setting.....	0.02 mm.	0.02 mm.	$\pm 0.04°$	$\pm 0.15°$
p_0........	Scale corrections.......	0.01 mm.	0.01 mm.	$\pm 0.02°$	$\pm 0.07°$
p_0........	Temp. of mercury......	0.03 mm.	0.03 mm.	$\pm 0.06°$	$\pm 0.23°$
p_0........	Barometer setting......	0.03 mm.	0.03 mm.	$\pm 0.06°$	$\pm 0.23°$
p_0........	Temp. of barometer....	0.03 mm.	0.03 mm.	$\pm 0.06°$	$\pm 0.23°$
p_0........	Variations in p_0........	0	0–.05mm.	0	0 to $\pm 0.3°$
p.........	Reference point........	0.02 mm.	0.02 mm.	$\pm 0.02°$	0
p.........	Manometer setting.....	0.02 mm.	0.02 mm.	$\pm 0.02°$	0
p.........	Scale corrections.......	0.02 mm.	0.02 mm.	$\pm 0.02°$	0
p.........	Temp. of mercury......	0.07 mm.	0.20 mm.	$\pm 0.07°$	$\pm 0.05°$
p.........	Barometer setting......	0.03 mm.	0.03 mm.	$\pm 0.03°$	$\pm 0.01°$
p.........	Barometer temp.......	0.03 mm.	0.03 mm.	$\pm 0.03°$	$\pm 0.01°$
p.........	Unheated space $\begin{cases} v_1 \\ t_1 \end{cases}$.....	0.020 cc. 0.5–50°	0.020 cc. 0.5°–100°	$\pm 0.07°$ $\pm 0.01°$	$\pm 0.5°$ $\pm 0.1°$
β.........	Temperature...........	1.0°	2.0°	$\pm 0.02°$	$\pm 0.11°$
β.........	Expansion.............	0.005mm.	0.008mm.	$\pm 0.02°$	$\pm 0.09°$
β.........	Hysteresis in expansion.	0.01 mm.	0.01 mm.	$\pm 0.04°$	$\pm 0.10°$
(C) E. M. F....	Instrumental correct'ns	1 mv.	2 mv.	$\pm 0.1°$	$\pm 0.2°$
E. M. F....	Contamination.........	0	0–12 mv.	0	0 to $+1.0°$
E. M. F.....	Integration over bulb..	3 mv.	12 mv.	$\pm 0.3°$	$\pm 1.0°$
(D) Fixed points	Instrumental correct'ns	1 mv.	2 mv.	$\pm 0.1°$	$\pm 0.2°$
Fixed points	Contamination.........	0	0–10 mv.	0	0 to $-1.0°$
Fixed points	Variation in given charge	Specific,	1–10 mv.	Specific,	0.1° to 1.0°
Fixed points	Variation between different charges........		Specific,	1–20 mv.	Specific, 0.1° to 2.0°

made, that the greatest present uncertainty in the high-temperature gas scale arises from the lack of uniformity in an air bath, which not only leads to uncertainty as to what is the true temperature of the gas in the bulb, but also to errors in the transference by the thermo-element. The next

largest uncertainty, due to the limitations in the purity and reproducibility of the substances available for fixed points, is not directly chargeable to the gas thermometer. In this connection, considerable more work needs to be done on the high thermometric points, comparable in thoroughness to the work in low-temperature thermometry of Richards, Dickinson, and others, on the sodium sulphate transition-point.

13. EXPERIMENTAL DATA AND CALCULATED RESULTS.

EXPANSION COEFFICIENT OF PLATINUM-RHODIUM.

In Table XI are given the experimental data on the expansion coefficients of the alloy 80 per cent platinum, 20 per cent rhodium. In the first column is given the date of the series, in the second and third columns the readings of the thermo-elements at the middle of the bar, corrected for zero error and the temperature of the cadmium cell. The 12 other readings taken with each element at each temperature at different points along the bar can not be given here,[1] but the fourth and fifth columns contain the readings of the thermo-element corrected to represent the integrated temperature along the bar. For convenience, the integration was made in terms of microvolts instead of degrees. The sixth and seventh columns contain the temperatures corresponding to the readings in columns 4 and 5, and the eighth column contains the mean of these two temperatures. The micrometer readings are not given, but in column 9 will be found the expansions reduced to millimeters for that portion of the bar lying between the o and 50 cm. marks on the ends. Each of these represents the mean of eight settings at each end of the bar. In the last column are given the values of the mean expansion coefficient from o°, calculated by dividing the expansion by the length at o° and by the temperature.

For convenience of comparison, the values of β at the nearest round temperatures were interpolated linearly between the observations in each series, and the results are given in Table XII. Values interpolated between these values are given in parentheses.

The table shows that the percentage error at 300° is greater than that at 1200° and above, probably on account of the larger effect of the hysteresis in the expansion and contraction, already discussed on page 63. The agreement of the results is very satisfactory, particularly in view of the fact that each series represents an entirely different curve of temperature variation along the bar. In some cases the temperatures at the end were lower than at the middle, in others higher than at the middle, and in one series one end was higher and the other lower. The mean of all, therefore, probably eliminates any error which might arise from variation of temperature along the bar.

The results are represented within the limits of error by the straight-line equation

$$10^6\beta = 8.79 + 0.00161t$$

[1] See p. 36 for an example of such readings, showing distribution of temperature in the case of the platin-iridium bar.

This may be compared here with the expansion coefficients between 300° and 1000° determined by the authors for the 10 per cent iridium alloy,[1] and by Holborn and Day[2] for the 20 per cent iridium alloy and for pure platinum:

$$80 \text{ Pt } 20 \text{ Ir}, \quad 10^6\beta = 8.20 + 0.00142t$$
$$90 \text{ Pt } 10 \text{ Ir}, \quad 10^6\beta = 8.84 + 0.00131t$$
$$\text{Pt}, \quad 10^6\beta = 8.87 + 0.00132t$$

TABLE XI.—OBSERVATIONS OF EXPANSION COEFFICIENT, β.

Date.	Thermo-elements.				Temperature.			Expansion from 0°.	
	W	Z	W cor.	Z cor.	By W	By Z	Mean.	Millimeters on 500 mm.	$10^6\beta$
					°	°	°		
1908.									
Sept. 21....	2261	2251	2312	2298	301.4	301.4	301.4	1.404	9.32
	3197	3187	3273	3258	404.6	405.4	405.0	1.912	9.44
	4169	4153	4257	4237	506.0	507.1	506.6	2.434	9.61
	5157	5140	5237	5212	603.9	605.1	604.5	2.950	9.76
	6197	6178	6286	6262	705.4	707.2	706.3	3.500	9.91
	7264	7238	7362	7333	806.2	807.8	807.0	4.064	10.07
	8361	8335	8457	8420	905.9	906.7	906.3	4.640	10.24
	9509	9470	9599	9552	1006.9	1006.8	1006.8	5.241	10.41
	10662	10611	10733	10675	1104.5	1103.4	1104.0	5.828	10.56
	11963	11896	12018	11921	1215.3	1210.2	1212.8	6.469	10.67
Sept. 25....	1817	1801	1848	1831	248.7	248.4	248.4	1.154	9.28
	2756	2735	2791	2768	353.4	352.9	353.2	1.666	9.43
	3699	3674	3726	3702	451.8	452.0	451.9	2.158	9.55
	4686	4655	4691	4662	549.7	550.3	550.0	2.668	9.70
	5711	5679	5691	5660	648.2	649.2	648.7	3.191	9.84
	6820	6788	6772	6742	751.2	752.6	751.9	3.757	9.99
	7847	7813	7754	7720	842.2	843.2	842.7	4.262	10.11
	8980	8945	8845	8809	940.8	941.4	941.1	4.827	10.26
	10140	10102	9939	9901	1036.4	1037.0	1036.8	5.403	10.42
	11368	11327	11109	11063	1136.9	1136.4	1136.7	6.012	10.58
Oct. 3......	2291	2272	2302	2283	300.3	299.8	300.1	1.384	9.22
	3228	3205	3250	3228	402.2	402.2	402.2	1.899	9.44
	4208	4181	4243	4215	504.6	504.9	504.8	2.432	9.63
	5205	5175	5247	5216	604.8	605.5	605.2	2.964	9.79
	6238	6206	6281	6249	704.9	705.9	705.4	3.511	9.95
	7297	7263	7342	7309	804.4	805.5	805.0	4.069	10.11
	8401	8365	8446	8408	904.9	905.6	905.3	4.644	10.26
	9536	9497	9576	9534	1004.9	1005.2	1005.1	5.231	10.41
	10675	10647	10710	10670	1102.6	1103.0	1102.8	5.830	10.57
	11884	11857	11926	11875	1207.5	1206.2	1206.8	6.466	10.71
Oct. 29.....	8419	8377	8366	8324	897.4	898.0	897.7	4.618	10.29
	9551	9507	9436	9392	992.6	992.8	992.7	5.169	10.41
	10706	10663	10539	10496	1088.0	1088.2	1088.1	5.752	10.57
	11884	11849	11786	11751	1195.6	1195.7	1195.7	6.401	10.70
	13137	13104	13134	13101	1309.9	1309.8	1309.9	7.154	10.92
1909.	W	D	W cor.	D cor.	By W	By D			
Oct. 13.....	2304	2301	2235	2232	293.0	293.0	293.0	1.352	9.23
	6222	6217	6180	6175	695.2	695.9	695.6	3.452	9.92
	9501	9494	9493	9486	997.6	998.1	997.9	5.190	10.40
Oct. 14.....	9540	9536	9542	9544	1001.9	1003.1	1002.5	5.200	10.37
	10666	10663	10690	10691	1101.9	1102.5	1102.2	5.811	10.54
	11839	11836	11783	11783	1195.4	1195.7	1195.6	6.410	10.72
	12998	12993	13121	13120	1308.9	1308.6	1308.8	7.156	10.93
	14183	14170	14390	14372	1413.4	1411.6	1412.5	7.832	11.09

[1] See pp. 27-39.
[2] Am. Jour. Sci. (4), 11, 374-390, 1901. Ann. d. Phys. (4), 4, 104-122, 1901.

TABLE XII.—VALUES OF $10^4\beta$ AT ROUND TEMPERATURES FOR THE ALLOY 80 Pt 20 Rh.

Temp.	21 Sept. 1908.	25 Sept. 1908.	3 Oct. 1908.	29 Oct. 1908.	13 Oct. 1909.	14 Oct. 1909	Mean.
250	....	9.28	....	....	....	....	....
300	9.31	(9.36)	9.22	....	9.24	....	9.28
350	(9.37)	9.43	(9.33)	....	(9.33)	....	9.36
400	9.43	(9.49)	9.44	....	(9.41)	....	9.44
450	(9.52)	9.55	(9.53)	....	(9.50)	....	9.52
500	9.60	(9.62)	9.62	....	(9.58)	....	9.61
550	(9.67)	9.70	(9.71)	....	(9.67)	....	9.69
600	9.75	(9.77)	9.79	....	(9.76)	....	9.77
650	(9.83)	9.84	(9.86)	....	(9.84)	....	9.84
700	9.90	(9.92)	9.94	....	9.93	....	9.92
750	(9.98)	9.99	(10.02)	....	(10.01)	....	10.00
800	10.06	(10.06)	10.10	....	(10.09)	....	10.08
850	(10.14)	10.12	(10.17)	....	(10.16)	....	10.15
900	10.23	(10.20)	10.25	10.29	(10.24)	....	10.24
950	(10.31)	10.27	(10.32)	(10.36)	(10.32)	....	10.32
1000	10.40	(10.36)	10.40	10.42	10.40	10.37	10.39
1050	(10.47)	10.44	(10.48)	(10.50)	....	(10.45)	10.47
1100	10.55	(10.52)	10.57	10.59	....	10.54	10.55
1150	(10.60)	10.60	(10.64)	(10.65)	....	(10.63)	10.62
1200	10.65	(10.67)	10.71	10.71	....	10.73	10.69
1250	....	....	....	(10.81)	....	(10.82)	10.81
1300	....	....	....	10.90	....	10.92	10.91
1350	....	....	....	(10.99)	....	(10.99)	10.99
1400	....	....	....	....	....	11.07	11.07
1450	....	....	....	....	....	....	(11.15)
1500	....	....	....	....	....	....	(11.23)

GAS-THERMOMETER DATA.

In Table XIII are given the observed gas-thermometer data.[1] In the first column is the date of measurement. The measurements are numbered chronologically in the second column for convenience of reference. In the third column is the measured pressure, p' (or p_0'), in millimeters of mercury at $0°$, corrected as described on pages 57–58. The application of the correction for unheated space (see p. 58) gives the pressure p (or p_0) which is found in the fourth column. In the fifth column is the value of the temperature, t, calculated by formula (5) on page 53. In column 6 are given the readings of the standard thermo-elements in microvolts, and in column 7 the positions of these elements on the bulb; for the significance of these figures see Fig. 8 and note on page 55. In the last column are given the other elements which were used on the bulb, together with their positions designated in the same way. The italicized letters represent single platinum wires instead of thermo-elements.

A few measurements in which the value of p_0 changed by more than 0.1 per cent have been omitted; their position is shown by the absence of their corresponding serial numbers.

[1] For the measurements in the table, seven furnaces were employed, using three different coils of platinum wire of about 400 grams each. One of these furnaces was wound on the outside, the other six on the inside of the tube. It was possible to rewind the wire at least once after the furnace had burned out. Failure always occurred several centimeters away from the bulb in the end portions of the furnace, which, in order to secure uniformity of temperature over the bulb, had to be considerably superheated. Only one measurement was made at the palladium point, as this one rendered the furnace unfit for further use; the conditions of this measurement were, however, perfect.

TABLE XIII.—OBSERVED GAS-THERMOMETER DATA.

Gas Filling No. 1.

Date.	No.	p' (or p₀')	p (or p₀)	t	Standard elements.	Position.	Other elements and positions.
1908.							
30 Nov......	1	217.65	217.63	0°	....		
30 Nov.....	2	1037.77	1042.72	1079.87	W 10443 / X 10491	4 / 8	Z (1), S (9)
1 Dec......	3	217.45	217.43	0	....		
2 Dec......	5	217.10	217.08	0	....		
3 Dec......	6	948.81	952.84	960.59	W 9061 / X 9100	4 / 8	Z (1), S (9)
4 Dec......	7	217.12	217.10	0	....		
16 Dec......	8	217.08	217.06	0	....		
17 Dec......	9	1038.50	1043.48	1083.61	W 10483 / X 10555	4 / 8	Z (1), S (9)
18 Dec......	10	217.18	217.16	0	....		
19 Dec......	11	1038.57	1043.56	1083.77	W 10473 / X 10512	4 / 8	Z (1), X (9)
21 Dec......	12	217.06	217.04	0	....		
23 Dec......	15	217.49	217.47	0	....		
24 Dec......	16	1242.38	1249.71	1365.71	A 13866 / X	4 / 8	Y (1), S (9)
28 Dec......	17	217.57	217.55	0	....		
1909.							
22 Jan......	18	1039.78	1044.74	1082.84	A 10502 / Y 10612	4 / 8	Z (9), B (1.3) W (2.3), S (6.7) X (7.3)
22 Jan......	19	1038.82	1043.79	1081.87	A 10506 / Y 10584	4 / 8	Do.
22 Jan......	20	1037.85	1042.83	1080.89	A 10498 / Y 10555	4 / 8	Do.
23 Jan......	21	217.36	217.34	0	....		
25 Jan......	22	543.01	544.07	418.40	A 3414 / Y 3436	4.5 / 8	Do.
25 Jan......	23	542.27	543.32	417.43	A 3408 / Y 3435	4.5 / 8	Do.
26 Jan......	24	703.78	705.81	629.80	A 5510 / Y 5550	4.5 / 8	Do.
26 Jan......	25	702.64	704.67	628.34	A 5501 / Y 5529	4.5 / 8	Do.
26 Jan......	26	949.56	953.63	960.22	A 9090 / Y 9159	4.5 / 8	Do.
26 Jan......	27	948.15	952.23	958.41	A 9075 / Y 9119	4.5 / 8	Do.
26 Jan......	28	1039.03	1044.05	1083.01	A 10515 / Y 10593	4.5 / 8	Do.
26 Jan......	29	1037.92	1042.93	1081.56	A 10505 / Y 10556	4.5 / 8	Do.
27 Jan......	30	217.33	217.31	0			
28 Jan......	31	542.87	543.92	418.30	A 3410 / Y 3436	4.5 / 8	Do.
28 Jan......	32	542.07	543.11	417.25	A 3404 / Y 3425	4.5 / 8	Do.
28 Jan......	33	704.06	706.07	630.21	A 5514 / Y 5553	4.5 / 8	Do.
28 Jan......	34	703.35	705.37	629.31	A 5510 / Y 5537	4.5 / 8	Do.
28 Jan......	35	948.96	953.05	959.46	A 9087 / Y 9142	4.5 / 8	Do.
28 Jan......	36	949.86	953.97	960.69	A 9098 / Y 9163	4.5 / 8	Do.
28 Jan......	37	1038.50	1043.57	1082.23	A 10511 / Y 10576	4.5 / 8	Do.

TABLE XIII—OBSERVED GAS-THERMOMETER DATA—Continued.

Gas Filling No. 1—Continued.

Date.	No.	p'(or p_0')	p(or p_0)	t	Standard elements.	Position.	Other elements and positions.
1909.							
28 Jan	38	1038.99	1044.06	1082.90	A 10512 Y 10585	4.5 8	Z (9), B (1.3), W (2.3),S(6.7)X(7.3)
28 Jan	39	1039.61	1044.68	1083.68	A 10509 Y 10617	4.5 8	Do.
29 Jan	40	217.37	217.35	0°	....		
29 Jan	41	949.32	953.38	959.78	A 9086 Y 9156	4.5 8	Do.
29 Jan	42	948.58	952.66	958.81	A 9085 Y 9131	4.5 8	Do.
29 Jan	43	1039.29	1044.34	1083.15	A 10515 Y 10595	4.5 8	Do.
29 Jan	44	1038.49	1043.56	1082.09	A 10511 Y 10568	4.5 8	Do.
29 Jan	45	1039.63	1044.71	1083.58	A 10508 Y 10617	4.5 8	Do.
30 Jan	46	217.39	217.37	0	....		

Gas Filling No. 2

Date.	No.	p'(or p_0')	p(or p_0)	t	Standard elements.	Position.	Other elements and positions.
1909.							
18 Feb	47	346.74	346.70	0	....		
22 Feb	48	346.78	346.74	0			
23 Feb	49	745.09	746.19	319.55	A 2487 D 2483 Z 2462	4.5 4.5 8	W (1.3), B (2.2), X (6.2), S (7.3), Y (12)
23 Feb	50	866.47	868.15	418.40	A 3414 D 3406 Z 3385	4.5 4.5 8	Do.
23 Feb	51	995.97	998.38	524.71	A 4451 D 4439 Z 4413	4.5 4.5 8	Do.
23 Feb	52	1122.39	1125.61	629.37	A 5510 D 5495 Z 5463	4.5 4.5 8	Do.
24 Feb	53	346.67	346.63	0			
26 Feb	59	346.24	346.20	0			
26 Feb	60	1657.03	1665.07	1083.17	A 10508 D 10473 Z 10422	4.5 4.5 8	W (3.3), B (2.2), X (6.2), S (7.2), Y (12)
27 Feb	61	346.45	346.41	0			
1 Mar	62	1388.84	1394.13	853.76	A 7895 D 7869 Z 7829	4.5 4.5 8	B (3.2), W (2.3), X (6.2), S (7.2), Y (12)
1 Mar	63	1513.67	1520.20	960.29	A 9086 D 9055 Z 9010	4.5 4.5 8	Do.
1 Mar	64	1632.03	1639.78	1062.15	A 10265 D 10229 Z 10178	4.5 4.5 8	Do.
1 Mar	65	1655.77	1663.81	1082.84	A 10511 D 10474 Z 10420	4.5 4.5 8	Do.
2 Mar	66	346.20	346.17	0	....		
3 Mar	67	1386.28	1391.55	852.44	A 7885 D 7861 Z 7820	4.5 4.5 8	W (3.3), B (2.2) X (6.2), S (7.2) Y (12)

TABLE XIII.—OBSERVED GAS-THERMOMETER DATA—Continued.

Gas Filling No. 2—Continued.

Date.	No.	p' (or p_0')	p (or p_0)	t	Standard elements.		Position.	Other elements and positions.
1909.								
3 Mar......	68	1511.95	1518.48	959.81	A	9088	4.5	W (3.3), B (2.2),
					D	9059	4.5	X (6.2), S (7.2),
					Z	9013	8	Y (12)
3 Mar......	69	1628.71	1636.46	1060.24	A	10257	4.5	Do.
					D	10221	4.5	
					Z	10169	8	
3 Mar......	70	1654.46	1662.50	1082.73	A	10512	4.5	Do.
					D	10478	4.5	
					Z	10444	8	
5 Mar......	71	345.98	345.94	0	....			

Gas Filling No. 3.

Date.	No.	p' (or p_0')	p (or p_0)	t	Standard elements.		Position.	Other elements and positions.
1909.								
4 June.....	72	345.31	345.27	0	....			
4 June.....	73	861.67	862.94	417.07	A	3403	4.1	Y (1), a (2.4),
					E	3419	4.3	b (6.4)
					F	3414	4.5	
					G	3416	4.7	
					Z	3370	8	
4 June.....	74	1118.50	1120.83	629.11	A	5516	4.1	Do.
					E	5535	4.3	
					F	5528	4.5	
					G	5529	4.7	
					Z	5461	8	
5 June.....	75	345.31	345.27	0	....			
5 June.....	76	1510.50	1515.27	959.77	A	9090	4.1	Do.
					E	9114	4.3	
					F	9099	4.5	
					G	9108	4.7	
					Z	9002	8	
5 June.....	77	1628.08	1633.64	1060.53	A	10258	4.1	Do.
					E	10285	4.3	
					F	10266	4.5	
					G	10279	4.7	
					Z	10161	8	
5 June.....	78	1652.36	1658.10	1081.28	A	10503	4.1	Do.
					E	10529	4.3	
					F	10510	4.5	
					G	10523	4.7	
					Z	10404	8	
7 June.....	79	345.50	345.46	0	....			
10 June.....	80	345.52	345.48	0	....			
18 June......	81	1512.96	1517.69	961.21	F	9120	4.1	a (1), b (2.4),
					E	9128	4.3	c (6.4), e (7.3)
					A	9080	4.5	
					G	9122	4.7	
					Z	9015	8	
18 June.....	82	1630.94	1636.53	1062.53	F	10299	4.1	Do.
					E	10300	4.3	
					A	10252	4.5	
					G	10292	4.7	
					Z	10181	8	
18 June.....	83	1653.61	1659.37	1082.14	F	10534	4.1	Do.
					E	10534	4.3	
					A	10487	4.5	
					G	10526	4.7	
					Z	10403	8	

TABLE XIII.—OBSERVED GAS-THERMOMETER DATA—Continued.

Gas Filling No. 3—Continued.

Date.	No.	p' (or p_0')	p (or p_0)	t	Standard elements.		Posi- tion.	Other elements and positions.
1909.								
18 June.....	84	1654.51	1660.27	1082.91	F E A G Z	10536 10534 10485 10525 10426	4.1 4.3 4.5 4.7 8	a (1), b (2.4) c (6.4), e (7.3)
19 June.....	85	345.51	345.47	o	....			

Gas Filling No. 3a.

Date.	No.	p' (or p_0')	p (or p_0)	t	Standard elements.		Posi- tion.	Other elements and positions.
1909.								
19 June.....	86	219.73	219.71	o	....			
19 June.....	87	710.34	711.83	627.61	F E A G Z	5520 5520 5484 5516 5437	4.1 4.3 4.5 4.7 8	a (1), e (2.3) c (6.3), f (7.3)
19 June.....	88	962.21	965.23	961.71	F E A G Z	9139 9136 9089 9131 9036	4.1 4.3 4.5 4.7 8	Do.
19 June.....	89	1051.74	1055.41	1082.75	F E A G Z	10540 10538 10490 10532 10428	4.1 4.3 4.5 4.7 8	Do.
21 June.....	90	219.74	219.72	o	....			
22 June.....	92	220.65	220.63	o	....			
24 June.....	93	220.62	220.59	o	....			
25 June.....	95	220.56	220.53	o	....			
2 July......	96	1283.36	1288.82	1391.97	H E F G Z	14251 14227 14222 14245 14121	4.1 4.3 4.5 4.7 8	Do.
2 July......	97	1285.43	1290.89	1394.89	H E F G Z	14282 14247 14241 14274 14156	4.1 4.3 4.5 4.7 8	Do.
3 July......	98	221.02	220.99	o	....			
3 July......	99	1281.97	1287.45	1393.34	H E F G Z	14213 14214 14196 14216 14099	4.1 4.3 4.5 4.7 8	Do.
3 July......	100	1284.05	1289.54	1396.17	H E F G Z	14264 14242 14235 14259 14156	4.1 4.3 4.5 4.7 8	Do.
6 July......	101	220.62	220.60	o	....			

TABLE XIII.—OBSERVED GAS-THERMOMETER DATA—Continued.

Gas Filling No. 4.

Date.	No.	p' (or p_0')	p (or p_0)	t	Standard elements.	Position.	Other elements and positions.
1909							
8 July......	102	216.81	216.79	o	....		
					H 14235	4.1	a (1), e (2.3)
					E 14216	4.3	c (6.3), f (7.3)
8 July......	103	1261.35	1266.80	1391.15	F 14209	4.5	
					G 14222	4.7	
					Z 14124	8	
					H 14249	4.1	Do.
					E 14229	4.3	
8 July......	104	1263.13	1268.59	1393.55	F 14199	4.5	
					G 14236	4.7	
					Z 14155	8	
9 July......	105	217.36	217.33	o	....		
					H 14251	4.1	Do.
					E 14236	4.3	
9 July......	106	1261.71	1267.15	1391.64	F 14233	4.5	
					G 14241	4.7	
					Z 14123	8	
					H 14240	4.1	Do.
					E 14236	4.3	
9 July......	107	1263.01	1268.46	1393.44	F 14225	4.5	
					G 14233	4.7	
					Z 14152	o	
10 July......	108	217.35	217.33	o	....		
					H 15019	4.1	Do.
					E 15020	4.3	
10 July......	109	1306.60	1312.52	1455.37	F	4.5	
					G	4.7	
					Z 14903	8	
12 July......	110	217.36	217.34	o	....		
					H 14978	4.1	Do.
					E 14980	4.3	
12 July......	111	1305.53	1311.35	1453.52	F	4.5	
					G	4.7	
					Z 14867	8	
					H 14980	4.1	Do.
					E 14960	4.3	
12 July......	112	1305.46	1311.28	1453.31	F 14947	4.5	
					G	4.7	
					Z 14872	8	
13 July......	113	217.40	217.38	o	....		
10 Sept......	114	217.38	217.36	o	....		
					H	4.1	a (1), c (2.3)
					E 15389	4.3	e (6.7), f (7.3)
11 Sept......	115	1328.68	1334.79	1484.70	F 15374	4.5	
					G	4.7	
					A 15357	8	
					H	4.1	Do.
					E 15411	4.3	
11 Sept......	116	1332.18	1338.32	1489.60	F 15417	4.5	
					G 15418	4.7	
					A 15421	8	
13 Sept......	117	217.62	217.60	o	....		
					H	4.1	a (1), c (2.3)
					E 15391	4.3	e (6.7) f (7.3)
15 Sept......	118	1329.92	1336.03	1487.36	F 15389	4.5	
					G 15399	4.7	
					A 15382	8	
16 Sept......	119	217.51	217.49	o	....		

Table XIII.—Observed Gas-Thermometer Data—Continued.

Gas Filling No. 4—Continued.

Date	No.	p' (or p_0')	p (or p_0)	t	Standard elements.	Position.	Other elements and positions.
1909 17 Sept	120	1329.68	1335.78	1486.95	H .... E 15386 F 15376 G 15368 A 15379	4.1 4.3 4.5 4.7 8	a (1), c (2.3) e (6.7), f (7.3)
17 Sept	121	1331.40	1337.51	1489.34	H .... E 15397 F 15396 G 15389 A 15412	4.1 4.3 4.5 4.7 8	Do.
18 Sept	122	217.52	217.50	0	....		
21 Sept	123	1306.75	1312.72	1454.83	H .... E 14991 F 14996 G 14957 A 14982	4.1 4.3 4.5 4.7 8	Do.
21 Sept	124	1307.28	1313.25	1455.60	H .... E 14979 F 14984 G 14952 A 14996	4.1 4.3 4.5 4.7 8	Do.
22 Sept	125	217.45	217.43	0	....		
27 Nov[1]	126	1045.80	1049.49	1090.59	H 10618 E 10626 F 10622 G 10616 C 10567	4.1 4.3 4.5 4.7 8	a (1.5), J (2.4) c (6.2), e (7.2)
29 Nov	127	217.28	217.26	0	....		
9 Dec	128	1129.52	1133.91	1206.63	H 12002 E 12006 F 12003 G 12010 C 11914	4.1 4.3 4.5 4.7 8	Do.
9 Dec	129	1194.81	1199.74	1298.01	H 13106 E 13112 F 13107 G 13115 C 13007	4.1 4.3 4.5 4.7 8	Do.
9 Dec	130	1261.16	1266.68	1391.45	H 14246 E 14250 F 14248 G 14256 C 14146	4.1 4.3 4.5 4.7 8	Do.
10 Dec	131	217.30	217.28	0	....		
20 Dec	132	1125.92	1130.29	1201.50	H 11940 E 11946 F 11951 G 11949 C 11887	4.1 4.3 4.5 4.7 8	a (1), J (2.3), c (6.2), e (7.1)
20 Dec	133	1302.40	1308.33	1450.03	H 14950 E 14958 F 14962 G 14955 C 14882	4.1 4.3 4.5 4.7 8	Do.
20 Dec	134	1372.16	1378.78	1550.15	H 16156 E 16160 F 16170 G 16148 C 16075	4.1 4.3 4.5 4.7 8	Do.
21 Dec	135	217.29	217.27	0	....		

[1] Outside-wound furnace. See p. 56 and Fig. 10.

14. THE TRANSFER TO THE FIXED POINTS.

After the thermo-elements are removed from the bulb, their E. M. F. at the fixed points must be determined by immersing them in melting or freezing metals or salts. The instrumental corrections to the readings so obtained were the same as in the case of the gas-thermometer readings. The error due to contamination was also present above 1100°, just as in the gas-thermometer furnace, and was a very disturbing factor in determining the melting-points of nickel, cobalt, and palladium. Its source, however, was not usually iridium vapor from the furnace or rhodium from the wire of the element, but was either vapor of the melting metal itself, or (when a hydrogen atmosphere was used) the products of reduction of silica. In the presence of hydrogen, silica rapidly deteriorates platinum wire by reduction and alloying, as has been shown in this laboratory by Shepherd,[1] and elsewhere by several observers. The contamination can be partly prevented by the use of a glazed procelain tube surrounding the thermo-element, instead of an unglazed magnesia tube; but an additional uncertainty is thereby introduced through the contamination of the melting metal by the melted glaze on the porcelain. For this reason nickel and cobalt did not prove to be as satisfactory fixed points as had been hoped, since it was necessary to melt them in an atmosphere of hydrogen. Palladium, however, can be melted in the open air and serious contamination by silicon thus be avoided, although the palladium itself gradually contaminates the wire.

Above 1100° it was found better to make direct comparisons of all the elements with one or two whose fixed points had been determined, rather than to contaminate them all by a direct determination. For making these comparisons, the plan first used was to bring a crucible of molten silver to a constant temperature and insert the elements (protected by a glazed Marquardt porcelain tube) successively into the silver bath. There is an uncertainty, however, in these measurements, of 2 to 3 microvolts caused by small differences of temperature within the tube and the slight cooling produced by introducing cold wires into the furnace. A better method is to join together the two platinum wires and the two alloy wires of the elements to be compared, and determine the small E. M. F.'s of each pair at several temperatures, from which the difference between the elements at those temperatures can be obtained by algebraic addition. This method offers a great advantage in that the temperature need be only approximately constant and approximately known, since the differences in most cases amount to only a few microvolts. By this method the comparison can be very quickly made at 1500° in the blast-lamp flame, which, with a little care, can be made to give a temperature constant to 20°.

All the metal melting-points here described, except that of palladium, were made in an upright cylindrical furnace through which passed a glazed porcelain tube which could be tightly closed above and below and therefore permitted the atmosphere about the melting metal to be perfectly controlled. An effort was first made to accomplish this by placing the entire furnace inside a gas-tight bomb in which the atmosphere could be similarly varied, but the persistent retention of gases by the various clay insulating

[1]Am. Jour. Sci. (4), 28, p. 300, 1909.

materials used about the furnace made this method slow, cumbersome, and very uncertain in its results. The only success which these bomb furnaces attained was to permit melting-points to be measured in an approximate vacuum (about 1 mm. pressure). But it has since been found so much simpler to operate with a neutral or reducing atmosphere in the closed tube passing through the heated zone that the vacuum furnace has not been used for this work.

The chief disadvantage in the use of a tube of this kind is its effect upon the temperature gradient along the furnace axis. More heat is diverted toward the ends of the furnace and the central constant-temperature zone becomes shorter. It offers no difficulty except that greater care must be taken in locating the crucible within the constant-temperature region.

The qualities desired in fixed thermometric points for establishing and reproducing a scale are:

(1) Exact reproducibility of the temperature in repeated determinations with the same charge of material and with a different charge independently obtained. This means that the metal or salt must be obtainable either perfectly pure or with a constant amount and kind of impurity.

(2) Independence of particular experimental arrangements. The melting-point of a metal, for instance, must be sharp and definite enough so that with different kinds of furnaces *and different rates of heating* the same temperature will be obtained.

(3) Convenience and safety of manipulation. A melting-point which can only be obtained by the use of elaborate experimental arrangements is undesirable, even though it be reproducible and sharp. Furthermore, the substance must not injure the instrument to be calibrated.

1. *Reproducibilty.*—No extensive experiments have been made in the present work to test a large number of samples of different origin. It appeared sufficient to assure ourselves that all of the metals here used are obtainable in such degree of purity, or with such a constant amount of impurity, that the variations in their melting-points are well within the limits of error in the scale itself. Waidner and Burgess[1] have recently made comparisons of various samples of pure zinc, antimony, and copper, and have found no differences exceeding 0.3°.[2] Our experience has been the same. All of the metals in the present investigation are readily obtainable from the ordinary sources of supply. They have been carefully analyzed in this laboratory by Dr. E. T. Allen, and the results are given on page 85.

2. *Independence of Experimental Conditions.*—A number of experiments were made to test the effect of different experimental arrangements on the points. Two different furnaces were tried, one 65 mm. inside diameter and 150 mm. long, the other 55 mm. inside diameter and 230 mm. long. The region of constant temperature in the second furnace was longer than in the first and accordingly there was a larger range in which the crucible could be moved about without affecting the temperature. This furnace was used for all work after March 6, 1909. The ultimate test was always the agreement between the melting and freezing points. Any serious disagreement of these two in metals shows that some influence is entering from without.

[1]Phys. Rev., 27, 467-469, 1909. Bull. Bur. Stds., 6, 149-230, 1909.
[2]In the case of antimony, this statement applies only to Kahlbaum's metal.

The results of the study were briefly as follows: (1) The best dimensions for a charge of metal are about 25 mm. diameter by 45 mm. deep. (2) The thermo-element tube should be about 5 mm. above the bottom of the crucible. (3) There is a region within the furnace in which the melting and freezing points agree and are independent of the rate of heating or (within limits) of the depth of immersion of the thermo-element; it is necessary to find this position of the crucible by trial. With this position once determined, the temperature of the zinc, antimony, silver, gold, and copper points can be relied upon within 0.2°. With large charges and facilities for stirring the metal, Waidner and Burgess have found the zinc point to be reproducible in a given furnace, with a given sample, within less than 0.1°.

White[1] showed that the temperatures of the two silicate points used for for the present scale are reproducible within 1.0° independently of the dimensions of the furnace or the rate of heating. For a mineral melting-point the charge should be small (about 3 grams), the heat should flow into the thermal junction from the side and not from the ends, and a position in the furnace should be found in which the melting-point, determined by a bare thermo-element, *does not vary with the rate of heating.*

The possibility has been several times suggested that the temperature of the thermo-element inside of the tube might possibly be lower by a small constant amount than the metal outside of the tube, and that this error might not be brought to light by such experiments as have been described. Several melting and freezing points of copper were therefore determined by inclosing the entire thermo-element wire in a thin capillary of silica glass which was slipped over the wire, bent double, and melted down upon the wire at the junction by heating in the oxy-hydrogen flame. This was dipped directly into the molten copper to within 5 mm. of the bottom, so that there was practically no possibility that the temperature of the junction could be lowered by radiation or conduction upward. The melting-point on element D obtained in this way was 10,473 microvolts as compared with 10,473 microvolts in the closed glazed tube. There appears to be no error from this cause.

3. *Convenience and Safety of Manipulation.*—Zinc and gold are the most convenient of manipulation, as they require no special atmosphere and the temperatures are easily reached. Antimony, silver, and copper require an atmosphere of carbon monoxide and are somewhat less convenient. More care needs to be taken with copper than with silver and antimony because of the considerable effect of a very small amount of oxide. Antimony, silver, gold, and copper were all melted in carbon monoxide, made by dropping formic acid into warm sulphuric acid, and purified by passage through sodium hydroxide, lead nitrate, and sulphuric acid. The lead nitrate was introduced to make certain that no trace of hydrogen sulphide, which might be formed if the acid became too dilute or too warm, could pass into the metal.

The two silicates (diopside and anorthite) and palladium were melted in air. The silicate points are very convenient to arrange and manipulate, provided the furnace is well insulated so that the temperature can be reached

[1] Diopside and its relations to calcium and magnesium metasilicates, Am. Journ. Soc. (4). 27. p. 4, 1909.

without difficulty. Palladium strains the platinum resistance furnace near
to its limit of endurance on account of the high temperature, but has the
great convenience of not requiring a reducing atmosphere. Special pains
need to be taken, however, in this case, to protect the thermo-element from
contamination.

Nickel and cobalt were melted in an atmosphere of hydrogen which was
made by electrolysis in a large glass and earthenware generator, and purified
by passage through potassium pyrogallate and sulphuric acid. Just before
the thermo-element was introduced, the hydrogen was displaced by pure
nitrogen drawn from a steel tank in which it was stored under pressure.
The supply contained a trace of hydrogen and was, therefore, purified by
passing over hot copper oxide and through calcium chloride and sulphuric
acid. The extreme lightness of hydrogen compared with the outside air
(especially when it is heated to 1450°) makes necessary special precautions
in order to keep out any trace of air. Furthermore, hydrogen always caused
contamination in the thermo-element, which was not prevented even when
the hydrogen was replaced for a short time during the melting by pure
nitrogen. Nickel and cobalt are, therefore, not recommended for frequent
use in the calibration of thermo-elements, if the two points, diopside and
palladium (or diopside and anorthite), give a sufficient calibration for the
purpose in hand

The apparatus used for the melting-points of nickel and cobalt is shown
in section in Fig. 13. The top of the large porcelain tube (Marquardt, glazed
outside only) was closed by a sliding cup of brass in which the thermo-
element tube and two others for introducing hydrogen were fastened by
heating the cup and pouring in molten solder. The porcelain tube extended
far enough out of the furnace to keep the brass cup cool. A groove near
the base of the cup carried a piece of asbestos cord which made a gas-tight
joint with the porcelain tube and permitted the whole to be raised and
lowered without moving the crucible or opening the top of the tube. Two
diaframs of Marquardt porcelain above the crucible also prevented any
considerable radiation upward to the brass cup.

In zinc, antimony, silver, gold, and copper, the thermo-element was pro-
tected by a glazed Marquardt tube of 5 mm. inside and 8 mm. outside
diameter. In the case of antimony, the tube was further protected by a
thin tube of graphite which fitted into the cover of the crucible. With
diopside and anorthite, some contamination from iridium in the furnace
may take place, but can be largely prevented by surrounding the supporting
tube with pure platinum. Here the thermo-element dips directly into the
molten silicate. A glazed Marquardt tube can not be used with the silicates,
for the glaze flows readily at these temperatures and may make its way into
the charge. With nickel and cobalt, glazed Marquardt tubes and also pure
magnesia tubes of the same size were used, but neither protects the element
perfectly from contamination. In palladium only the pure magnesia tubes
were used.

Zinc, antimony, silver, gold, and copper were melted in graphite crucibles
27 mm. in diameter and 80 mm. deep inside, and 37 mm. in diameter and
100 mm. high outside. The charge of metal was from 45 mm. to 55 mm.
deep. Diopside and anorthite were melted in small platinum crucibles 10

mm. in diameter and 18 mm. deep, suspended by platinum sleeves from the open end of unglazed Marquardt tubes, as described and illustrated in the paper already referred to.[1]

Nickel was melted in an unglazed Marquardt porcelain crucible, lined with a paste consisting of about 90 per cent Al_2O_3 and 10 per cent MgO; and also in a Berlin "pure magnesia" crucible. The charge was about
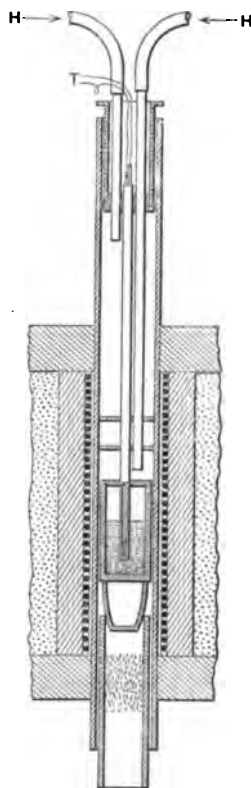
Fig. 13. The furnace in which the cobalt and nickel melting-points were made, showing the position of the metal with respect to the coil, the thermo-element (T) and the arrangement (H) for maintaining a hydrogen or nitrogen atmosphere.

25 mm. in diameter and 30 mm. deep. Cobalt could not be melted in the alumina-lined crucible, as the metal penetrated through the lining and attacked the porcelain. It was, therefore, melted in a "pure magnesia" crucible made by the Königliche Porzellan Manufaktur. The material of these crucibles probably contains a small percentage of silica. Palladium was melted in a crucible made in this laboratory from a specially pure magnesia made by Baker and Adamson. The magnesia was first shrunk by heating to a temperature higher than that at which the crucible was to

[1] W. P. White, Am. Jour. Sci. (4), 28, p. 477, 1909.

be used, and was then made into a paste with water and a little magnesium chloride, spun into form, and baked.

In choosing the materials for such determinations, two not altogether concordant standpoints must be recognized: (1) The materials used must be of absolutely known composition and of high purity in order to give the melting-point determinations a positive significance; (2) the same materials in the same purity must be easily obtainable by other investigators in order to enable the results to be conveniently utilized by others if desired.

Metal melting-points were given the preference over pure salts which have been repeatedly suggested for this purpose, (1) on account of the greater sharpness of the melting-point, (2) on account of their general availability for such determinations, and (3) because of the now very generally established custom of comparing the results of different observers through the medium of these standard melting-points. The metals used in this investigation were from various sources, which will be specified below. Each has been very carefully described and analyzed by Dr. E. T. Allen of this laboratory, whose report is printed in full on page 85 and following. We prepared none of the metals ourselves. Those which were used were purchased from firms who may fairly be expected to supply the same nominal quality to any other investigator who may care to use them, but it must be emphasized in this connection that metals furnished under the same description by the same dealer at different times have not always proved of uniform purity and probably can not at present be expected to be so. The variations in the thermal behavior of the different samples is not great, never amounting to more than 1° in our experience; but we are of course unable to offer any guarantee that the same metals obtained in future will remain within this limit, nor is the dealer's guarantee at present a sufficient protection.

As the situation now stands, the errors in the gas-thermometer measurements are of the same order as the differences between the melting-points of different samples of a given metal obtained at different times from the same dealer and of the same (nominal) purity. This may serve to emphasize more than ever before the desirability of a provision, preferably by some national bureau of standards, for standard metals, the uniform purity of which can be absolutely depended upon, and in terms of which such constants can be expressed. In the absence of such a provision, it is difficult to see just how to make the gas scale conveniently available for general use in its full accuracy. This is furthermore a matter of considerable importance in view of the extended extrapolation to which the gas scale is frequently subjected by the use of thermo-elements or otherwise. Supposing the metal melting-points to be capable of reproducing the temperature curve correctly within 1° at the copper point (1082.6°), an extrapolation to 1500° may easily remain uncertain by as much as 10° in the hands of different individuals using the same function for the extrapolation.

15. THE METALS USED.

(By E. T. Allen.)

The object of these analyses was primarily, of course, to decide whether the metals should be used or rejected for the temperature scale, and those selected were examined very carefully, so that in the future, when more is known about the specific lowering which the various impurities produce on the melting-point, corrections may be made if desirable. The methods used in these analyses are given in so far as it has been deemed necessary. Details, especially in those cases where well-known procedure is followed, have been purposely omitted.

The accuracy of the determinations can not be stated absolutely. There is of course the possibility of increased solubility of difficultly soluble compounds in the comparatively concentrated solutions of the metals from which the impurities have to be precipitated, viz, 5 to 6 g. in 250 cc. volume. Also, when it is necessary to separate the bulk of the metal by precipitation from the impurities, as it sometimes is, one can not be sure that the impurity sought is not occluded by the precipitates. In most cases, the latter source of error is probably the more serious. Only methods worked out synthetically with materials laboriously prepared could decide these questions.[1] Large quantities of metal, 25 to 100 g., were generally taken for analysis, and since the impurities were weighed to the tenth of a milligram, the results are generally stated to the ten-thousandth of 1 per cent. This does not mean that the results are considered accurate to this figure. The variation in successive determinations comes in the thousandths, so that the fourth decimal place may have about as much value as the second in an ordinary analysis. Great pains have been taken to purify precipitates, often by many precipitations, so that in all cases the figures given may be regarded as minima. In all cases, too, I have endeavored to avoid missing anything, by repeating every process, rejecting no precipitate or solution until it was decided that nothing more was to be gotten from it. In any reasonable case of suspicion, blank determinations were made with the reagents.[2]

CADMIUM.

Eimer and Amend's "Cadmium metal sticks" purchased in 1904 was used. Inasmuch as the cadmium melting-point was used for the purpose of extrapolation only (p. 116) and but a single gas-thermometer measurement made upon it, less care was necessary in the analysis of it than in the more important metals which follow. The details are accordingly omitted. Its analysis is given on page 86.

[1] The data on this question which are known to me are quite meager. An interesting instance is given by Mylius and Fromm (Z. anorg. Chem. 9, 144–147, 1895), using a specimen of zinc in which they could detect no impurities. Additions of only 0.1 mg. of lead, cadmium, or mercury to a solution of 40 grams of this zinc could be detected qualitatively.

[2] After considerable experience in the examination of these "pure" metals the writer has reached the conclusion that a 10-gram portion, in the great majority of cases, will give as satisfactory results as a larger portion and with far less labor.

ANALYSIS OF CADMIUM.

As.. None
Cu.. Trace
Pb... .0860
Zn.. Trace
Fe... .0025
Co.. None
Ni.. None
S.. .0005

Total impurities................................... .0890 per cent.

ZINC.

This metal was obtained in the form of sticks from the firm of Eimer and Amend. The method of Mylius and Fromm was followed for the principal impurities.[1] 100 grams were dissolved in nitric acid. The solution was then diluted and ammonia was added until the zinc at first precipitated was entirely redissolved. Then enough hydrogen sulphide was added to throw down all the impurities of the hydrogen sulphide and ammonium sulphide groups together with considerable zinc. The precipitate was filtered off and further separations were made as usual.

The platinum metals and gold were not looked for, as it was thought quite improbable they would be present, but arsenic and antimony were sought for by Günther's method.[2] This consists in the volatilization of the hydrides of these metals which are separated from the hydrogen, which forms at the same time, by passing the gas through silver-nitrate solution. A special form of apparatus was used which consists of a 1-liter round-bottom flask with long neck 35 mm. wide at the top. This is closed by a glass stopper in which are sealed a small glass tube passing to the bottom of the flask and serving to fill the flask with hydrogen and to replace the gases formed in the experiment; a dropping funnel through which the acid used to dissolve the zinc is introduced, and lastly, an upright outlet tube surrounded by a small condenser. The outlet was connected with a wash bottle containing a solution of silver nitrate. As pure zinc dissolves with difficulty in dilute hydrochloric acid, the metal was reduced to the form of shavings by the aid of a lathe. Fifty grams of these shavings were introduced into the flask, the air in which was at once replaced by hydrogen. Dilute hydrochloric acid was then let in through the dropping funnel. The solution was facilitated by warming. At the end of the operation, the gas in the flask was driven out by pure hydrogen. The silver-nitrate solution, which contained a black precipitate, was then filtered. The antimony in the precipitate was determined by dissolving it in nitric acid with the addition of a little tartaric acid, precipitating the silver with hydrochloric acid, evaporating the filtrate to dryness on the steam bath, and precipitating by hydrogen sulphide. The precipitate was dissolved in a few drops of ammonium sulphide, the solution filtered into a small tared porcelain capsule, evaporated, decomposed by nitric acid, and weighed as Sb_2O_4. After separating the silver from the first filtrate which contained the arsenic, it was evaporated to dryness, reduced with sulphurous acid, and precipitated by hydrogen sulphide. None was detected with certainty.

[1] Zeitschr. anorg. Chem., 9, 144, 1895.
[2] Lunge, Chem.-tech. Methoden (1905), ii, 322. Zeitschr. analyt. Chem., 20, 503–507, 1881.

If this solution had been tested by Marsh's method, no doubt a trace would have been found, but as its quantity was of a different order of magnitude from the other impurities it was not thought worth while to make the test. Günther determines sulphur at the same time with arsenic and antimony, by interposing between the generator and the absorption cylinder which contains the silver nitrate another cylinder containing potassium-cadmium cyanide, which absorbs all the hydrogen sulphide and, according to him, retains no arsenic and antimony. Since a solution of this cadmium compound is always alkaline, it was thought safer to take a separate portion of zinc for the estimation of sulphur, silver nitrate being used as the absorption reagent. The small precipitate was examined for sulphur by dissolving in nitric acid and proceeding as usual. Found 0.4 mg. $BaSO_4$. Blank gave 0.3 mg. $BaSO_4$.

The zinc was tested for silicon in the same way as the copper. (See p. 92.)

ANALYSIS OF ZINC.

As	Not found
Sb	.002
Sn	Not looked for
Au	Not looked for
Pt	Not looked for
Ag	None
Bi	None
Pb	.051
Cd	.004
Ni	None
Co	None
Fe	.006
Si	None
S	None

.063 per cent.

ANTIMONY.

Twenty-five grams of metal were powdered in an agate mortar and treated with 35 per cent HNO_3 on the steam bath. As soon as the reaction was practically complete, the antimonic acid was extracted with hot dilute nitric acid, transferred to a filter, and washed with water. The filtrate and washings were then evaporated to dryness with hydrochloric acid, while the antimonic acid was digested repeatedly with yellow sodium sulphide till the soluble portion was dissolved. The residue, after a little washing, was dissolved in nitric acid, evaporated to dryness, freed from nitric by hydrochloric acid, and the chlorides united with the first extract. The whole was precipitated by hydrogen sulphide. The washed sulphides were then extracted with colorless ammonium sulphide. From this solution the sulphides were thrown down by acid, filtered, and washed. Then they were dissolved in hot dilute caustic potash. The solution was boiled with perhydrol for complete oxidation, and arsenic sought for by Fischer's method, viz, reducing by ferrous ammonium sulphate and distilling in a current of hydrochloric acid gas. No As.

A separate portion of 5 grams was taken for tin. McCay's method[1] was tried. $SnO_2 = 1.3$ mg. Sn = 1.0 mg. = 0.02 (?) per cent.

A separate portion of 25 grams was used for sulphur. The metal was oxidized by nitric acid as before, and the soluble portion separated and

[1] Private communication.

evaporated. The residue was then heated with a small excess of sodium carbonate and filtered. The residue was also boiled out several times with sodium carbonate solution. The two solutions were then acidified with hydrochloric acid and treated with barium chloride. The portion soluble in nitric acid gave a slight precipitate, which was further purified, after the usual washing and drying, by fusion with sodium carbonate. The water extract containing the soluble sulphate was acidified and precipitated a second time. $BaSO_4 = $ trace.

ANALYSIS OF ANTIMONY.

As	None
Sn	0.02 (?)
Ag	None
Pb	Trace (?)
Cu	0.004
Bi	None
Cd	None
Ni	None
Co	None
Mn	None
Zn	None
Fe	0.007
S	Trace (?)
	0.031 per cent.

ALUMINUM.

Owing to the difficulty of handling this metal, small portions (10 grams) only were taken for analysis. Heavy metals, except arsenic and antimony, were sought for in the hydrochloric acid solution by ordinary methods. Only a trace of copper was found.

For phosphorus, arsenic, and sulphur, a separate portion was dissolved in caustic alkali in a special apparatus entirely of glass. The vessel was first filled with purified hydrogen and then the alkali was introduced and the gases evolved were passed through silver-nitrate solution. At the end, the gases remaining in the vessel were displaced by hydrogen. The precipitated silver was worked over for the different elements. No As or Sb. A separate portion was used for sulphur. $BaSO_4 = 1.4$ mg. $S = 0.002$ per cent.

To determine the silicon, 10 grams of metal were dissolved in a mixture of nitric and sulphuric acids, using a platinum dish. With hydrochloric acid alone nearly all the silicon is lost as hydride. The brown amorphous residue was filtered, washed, and fused with sodium carbonate. From the fusion silica was obtained in the usual way. $SiO_2 = 41.4$ mg. $Si = 0.194$ per cent. Repetitions gave 0.189 per cent and 0.190 per cent.

For the carbon, 10 grams of metal were dissolved in NaOH and filtered through glowed asbestos, washed first with water, then with dilute acid, finally with water, and dried at 105°. The asbestos and residue were then transferred to a combustion tube and burned in air free from CO_2. The gases were passed through standard $Ba(OH)_2$. A considerable precipitate was obtained, while a blank gave no trace. The excess of $Ba(OH)_2$ was then titrated with standard acid, using phenolphthalein as indicator. 5.05 mg. CO_2 found. $C = 0.014$ per cent. A duplicate in which the metal was dissolved in KOH gave 0.012 per cent.

For the iron, 10 grams of metal were dissolved in hydrochloric acid, and to the solution was added tartaric acid free from iron. From this solution the iron was precipitated by colorless ammonium sulphide. The precipitate was finally changed to sulphate and determined volumetrically. Fe= 4.6 mg. Blank determination gave 0.3 mg. Fe= 0.043 per cent.

Calcium, sodium and potassium were sought for in the hydrochloric-acid solution, by precipitating with ammonia, washing the large precipitate, and testing the evaporated filtrate. No Ca. Some alkaline chloride was found, but a blank showed that it came from the ammonia, as there was only a difference of 1.6 mg. between the chloride of the blank and that in the determination. No Na or K.

ANALYSIS OF ALUMINUM.

As	None
Sb	None
P	None
Cu	0.003
Fe	0.043
Si	0.190
C	0.013
S	0.002
Ca	None
Na	None
K	None
	0.251 per cent.

SILVER.

This metal, as well as the gold, was prepared by Mr. Eckfeldt at the Philadelphia Mint. A block weighing about 100 grams was cut from a larger brick with a hard cold chisel and, after cleaning, transferred to a large casserole of Berlin porcelain and dissolved in a slight excess of nitric acid. During the operation the dish was covered with a watch-glass. A small black residue was now filtered off on the felt of a large porcelain Gooch crucible, then washed and dried. The asbestos of the felt was previously heated to redness. The residue was then laid in a porcelain boat which was slipped into a combustion tube containing copper oxide and heated in a current of oxygen. The outflowing gas was passed through a very dilute standard solution of barium hydroxide, 1 cc.= 0.97 mg. of CO_2, in which a decided white precipitate appeared at once. The excess of baryta was then titrated with standard acid. A blank determination *previously* made gave no precipitate in the baryta water. This determination is of no importance as regards the melting-point of the silver, since the metal had to be melted in graphite, but considering the source of the silver and its unusual degree of purity the determination may be of some interest. What remained of the residue after the carbon was burned was extracted with aqua regia. The solution was evaporated to dryness and taken up with hydrochloric acid, and the gold was precipitated by sulphur dioxide. The filtrate from gold gave a slight black precipitate with hydrogen sulphide. This precipitate weighed only 0.1 mg. after it had been glowed in a small porcelain crucible, but it remained black, dissolved in a few drops of aqua regia which left a yellow stain when evaporated, and gave a very strong rose color when dissolved in water and tested with a drop of potassium iodide—all character-

istic of platinum. It was suspected that a trace of platinum might exist in the acid used to dissolve the silver, but a blank test on the same quantity of reagent proved the contrary. The silver solution was now diluted to several liters and precipitated with hydrochloric acid. The filtrate was evaporated in porcelain to a small volume and in this the remaining impurities were sought for by well-known methods. Only lead and iron and the merest trace of copper were found.

A blank determination was made for iron. Found in the silver+reagents 0.0013 per cent; in the reagents, 0.0002 per cent; leaving 0.0011 per cent in the silver.

For the estimation of sulphur, a separate portion of 38 grams was taken, the silver was removed in the same manner, and the filtrate evaporated to dryness in porcelain. The small residue was then evaporated again with hydrochloric acid to decompose nitrates. The final residue was dissolved in a small volume of water acidulated with hydrochloric acid, filtered to remove any silver chloride which might have escaped precipitation, and precipitated with barium chloride. Found 1.4 mg. $BaSO_4$, while the same quantity of reagents gave 0.4 mg. $BaSO_4$: S=0.0004 per cent.

ANALYSIS OF SILVER.

As	None	Hg	None
Sb	None	Cd	None
Sn	None	Zn	None
Au	.0005	Ni	None
Pt	.0001	Co	None
Cu	Mere tr.	Fe	.0011
Bi	None	S	.0004
Pb	.0008	C	.0003

0.0032 per cent.

GOLD.

About 350 grams of "proof gold" were obtained from the Philadelphia Mint. It was prepared by Mr. Jacob Eckfeldt. A sample of gold prepared in a similar manner by Mr. Eckfeldt was used by Professor Mallet in his determination of the atomic weight of this metal. The method of purification is given in the Am. Chem. Jour., VII, 73, 1899. Professor Mallet found no systematic difference between this gold and two other samples, one of which was obtained from the Mint of England, and the other of which was prepared by himself. In view of these facts, it was evidently unnecessary to analyze the gold.

COPPER.

The copper was of the form known as "copper drops cooled in hydrogen" and was obtained from Eimer and Amend of New York. Not all copper of this brand is equally pure. The sample analyzed was a portion of a 25-pound lot. The method followed in the analysis was essentially that of Hampe,[1] in which the copper is separated from the impurities by precipitation as cuprous thiocyanate. A 100-gram portion was placed in a large casserole of Berlin porcelain, dissolved in nitric and sulphuric acids, and

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[1] Lunge; Chem.-tech. Methoden (1905), vol. II, 202. Chem. Ztg. 17, 1691-1692, 1893.

the solution was then evaporated to drive off the excess of nitric acid. This troublesome operation can be greatly facilitated by the use of a crown burner, though, as dilution and evaporation have to be several times repeated, small losses are difficult to prevent. Duplicate determinations, however, proved that they were entirely negligible as regards the small percentage of impurities. The sulphate of copper was now dissolved in water and diluted. A little HCl was added and, after standing, the solution was filtered. The residue left on the filter was extracted with ammonia to remove silver chloride and the remaining part of it was treated with aqua regia. There was still left a little silica, from the porcelain dish in which the copper was dissolved. The solution obtained by aqua regia after the nitric acid was entirely driven out by hydrochloric acid was tested for gold by sulphur dioxide. There was no precipitate in the cold even after long standing, though evaporation caused the precipitation of about 0.5 mg. of black metal. This remained black on heating, dissolved only partially and with difficulty in aqua regia, and with sulphuric acid and ammonium nitrate gave a faint blue color. These tests indicate iridium, though there was too little to identify with certainty. The rest of the solution which had been tested for gold was precipitated by hydrogen sulphide and the precipitate was filtered, washed, and burned in a porcelain capsule. It formed a yellow chloride with aqua regia, gave a precipitate with ammonium chloride and a very strong test for platinum with potassium iodide. This platinum did not come from the acids used to dissolve the copper, since the same quantities were very carefully tested by hydrogen sulphide after nearly the whole portion had been driven off by heating in porcelain, and were found to contain not a trace.

The solution containing the copper was then warmed and saturated with sulphur dioxide. After standing, a further portion of silver was precipitated, filtered off, and washed. It was then dissolved in a little nitric acid, precipitated again as chloride, and added to the main portion of the silver chloride, which was dried at 130° and weighed.

The solution still containing the copper was diluted to about 8 liters, and from it all but a small portion of the copper was precipitated by a standard solution of potassium thiocyanate, 1 cc. of which was equivalent to about 50 mg. of copper. The thiocyanate was proved to be free from heavy metals by a test with hydrogen sulphide. The small amount of iron which it contained was separated before the solution was standardized, by the addition of a little ammonium alum followed by ammonia. The solution was allowed to stand and then filtered from iron and alumina. The precipitation of the copper was done very gradually with constant shaking to avoid carrying down the impurities, and after long standing was filtered. The filtrate was concentrated to a small volume in porcelain. A small additional precipitate which came down in this process was worked over with care to avoid any possible loss of impurities, especially lead, though no metal but copper was found in it. The filtrate was then examined as usual.

A word is needed in reference to the presence of zinc. This was found in every sample examined, in fact, it was generally the chief impurity. It was suggested that this zinc, or at least a part of it, might have come from the large flasks of Jena glass in which the acid solutions of the copper stood.

To test this point, a sample of copper in which had been found 0.089 per cent of zinc was tested again. In this determination Jena glass was entirely discarded. The zinc found was 0.091 per cent. As these results agree within the limits of error, it is evident that Jena glass under these conditions will not contaminate solutions with zinc, at least in quantities of this order of magnitude. For the determination of silicon in the copper, 25 grams were placed in a platinum basin, dissolved in nitric and sulphuric acids, and evaporated over a crown burner to white fumes. The residue was dissolved and filtered. The filter was burned and the small residues tested for silica by hydrofluoric and sulphuric acids. Since it was feared that some silica might come from the watch glass used to cover the platinum dish during this operation, a blank was carried out with the reagents under the same conditions. Within the limits of error none was found.

For the estimation of sulphur the method of Lobry de Bruyn[2] was used, in which the copper is separated from the nitric acid solution by electrolysis. Twenty-five grams of metal was dissolved in 75 cc. nitric acid diluted with about an equal quantity of water, and then the excess of acid evaporated as far as possible on the steam bath. The electrolysis was done in a large platinum basin, which served as a cathode. The basin was covered with a glass plate pierced to admit a cylindrical platinum crucible which formed the anode. The current density was about 0.015 $\frac{amp.}{sq.\ cm.}$. After a time it was found necessary to pour off the solution from the precipitated copper and remove the free acid by another evaporation. A repetition of this operation is advisable. The filtrate from the copper is evaporated to dryness in porcelain and the small residue of nitrates decomposed by hydrochloric acid. The final residue is dissolved in acidulated water and precipitated by barium chloride.

Found in 25 grams copper......................... 4.2 mg. BaSO$_4$
Found in 75 cc. nitric acid......................... 0.6 mg. BaSO$_4$
3.6 mg. BaSO$_4$ = 0.002 per cent.

ANALYSIS OF COPPER.

As	None	Bi	None
Sb	None	Pb	None
Sn	None	Cd	None
Se	None	Zn	.0007
Te	None	Ni	None
Au	None	Co	None
Pt metals	.0011	Fe	.0038
Ag (separate determinations).. {.0007 / .0005}		Si	None
		S	.0020

0.0083 per cent.

NICKEL.

Two 50-gram portions of Kahlbaum's electrolytic nickel were dissolved separately in measured quantities of nitric acid and then carried to white fumes with excess of sulphuric acid. Both portions were then dissolved in water and filtered. There was a small dark residue which was washed thoroughly and extracted with aqua regia, leaving a little silica from the dish. The yellow chloride obtained was freed from nitric acid, saturated with SO$_2$, and left to stand. No gold. Changed to chloride again and tested with caustic soda and H$_2$O$_2$. Still no gold. Acidified and repre-

[2] R. des trav. chim. de Pays-Bas, 10, 125, 1891.

cipitated with NH_4Cl, a characteristic yellow precipitate was obtained. Confirmed by dissolving the chlor-platinate in hot water and precipitating by hydrogen. $Pt = 2.3$ mg. $= 0.0023$ per cent. The main solution was then precipitated by H_2S (volume, 2 liters). The small black precipitate obtained was worked over for gold and platinum together with the above.

Other heavy metals were tested for in the ordinary way. 0.2 mg. $PbSO_4 =$ about 0.1 mg. Pb. $Cu = 52.3$ mg. $= 0.0523$ per cent.

Ammonium Sulphide Group.—The voluminous solution was now freed from hydrogen sulphide by evaporation, some ammonium persulphate was added, and a stream of air passed through the solution for some time. No manganese.

$Fe_2O_3 = 6.1$ mg., after repeated precipitation. $Fe = 4.2$ mg.

Repeated efforts were made to separate zinc with H_2S on the principle of the lower solubility of ZnS in dilute acids, but without satisfaction. First I tried to precipitate a small fraction of the nickel, hoping to get all the zinc with it. The volume of the solution was about 5 liters. But unless so much acid was added that strong doubts were entertained of recovering any zinc that might be present, the fraction of the nickel precipitate was far too great. Again, all the nickel was precipitated and the precipitate was digested with cold 10 per cent solution of hydrochloric acid. Here one had to fear either the failure to remove the zinc or the removal of too much nickel to handle without so many precipitations that a small quantity of zinc would probably be lost. It is doubtful whether we have any method which will give very small amounts of zinc in metallic nickel.

The whole solution was now tested for cobalt as follows: It was freed from H_2S by evaporation, acidulated with HCl, and precipitated by a-ni-troso-β-naphthol in 50 per cent acetic acid. This was added in several portions. After long standing the precipitate was collected and washed. The voluminous precipitate was very cautiously burned in a capacious porcelain crucible. Much tar was formed. The residual oxide was dissolved in nitric acid and the cobalt was separated from nickel by KNO_2 in the usual way. The potassium cobalto-nitrite was finally decomposed by sulphuric acid and precipitated electrolytically from ammoniacal solution.

$Co = 101.4$ mg. $+ 4.9$ mg. recovered from filtrate and weighed as sulphate. Total $= 0.1063$ per cent.

Fe and Co were also determined in a separate 10 g. portion of metal. $Fe_2O_3 = 0.7$ mg. $Fe = 0.49$ mg. $= 0.0049$ per cent. $Co = 10.3$ mg. $= 0.1030$ per cent.

A separate 10-gram portion was taken for sulphur. It was dissolved in nitric acid and evaporated on the water bath. This solution was diluted and precipitated with a slight excess of sodium carbonate. The filtrate was just acidulated, evaporated, and treated with barium chloride. No precipitate.

ANALYSIS OF NICKEL.

Au	None	Bi	None
Pt	.0023	Cd	None
As	None	Zn	None found
Sb	None	Co	.1063
Sn	None	Mn	None
Pb	.0001	Fe	.0042
Cu	.0523	S	None

0.165 per cent.

COBALT.

Two 25-gram portions of Kahlbaum's metallic cobalt in the form of powder were dissolved in 150 cc. water+35 cc. concentrated H_2SO_4. The analysis was quite similar to that of the nickel.

In the H_2S group were found: $Cu = 8.9$ mg. $= 0.0178$ per cent. $PbSO_4 = 12.9$ mg. $Pb = 0.0176$ per cent.

In the $(NH_4)_2S$ group manganese was tested for as in the nickel. None was found. $Fe_2O_3 = 0.9$ mg. $Fe = 0.0006$ per cent.

As the tests for Ni and Zn were unsatisfactory, another portion of 25 grams was dissolved in dilute sulphuric acid and precipitated by H_2S.

The filtrate from the sulphides was filtered and freed from excess of H_2S by evaporation. Then it was diluted to 1 liter and divided into two portions. Both were neutralized by sodium carbonate. In the one, manganese was sought for by ammonium persulphate. In the other nickel was looked for. A little ammonia was added and then an alcoholic solution of dimethylglyoxime. A precipitate containing much cobalt was obtained. This was worked over for nickel but none was found. For sulphur the method used in the analysis of nickel was followed. $BaSO_4 = 14.4$ mg., blank $= 5.1$ mg., difference $= 9.3$ mg., $S = 0.013$ per cent.

ANALYSIS OF COBALT.

Ag	None	Bi	None
Au	None	Cd	None
Pt	None	Zn	None
As	None	Ni	None
Sb	None	Fe	.0006
Sn	None	Mn	None
Pb	.0176	S	.013
Cu	.0178		

0.049 per cent.

HERAEUS'S PALLADIUM.

The palladium was naturally suspected to contain other metals of the platinum group. It is well known that the separation of these metals is a problem of unusual difficulty. The plan here was therefore to precipitate most of the palladium from solution as one of its characteristic compounds and, while the filtrate was reserved for impurities, to redissolve and again precipitate the metal as another characteristic compound. In this way it was hoped that those impurities retained by the first precipitate would not be occluded by the second The sheet metal was first cut into shavings on a milling machine especially cleaned for the purpose. Then the shavings were boiled a short time with dilute hydrochloric acid to remove any iron from the surface, and then washed and dried. After an unsuccessful endeavor to dissolve the palladium in nitric acid (insoluble brown hydroxide (?) always formed), it was dissolved in aqua regia and rid of nitric acid by successive evaporations with excess of hydrochloric acid. It was then dissolved in dilute hydrochloric acid and diluted further to about one liter. Ammonia was added in excess.[1] A precipitate came down and redissolved on warming, all but a little ferric hydroxide, which was filtered off. The filtrate was then evaporated again to about 250 cc., and then diluted and precipitated

[1] E. F. Smith and H. F. Keller, Amer. Chem. Jour., 14, 423, 1892.

with stirring, by dilute hydrochloric acid. The voluminous precipitate of $PdCl_2$. $2NH_3$ was now filtered and washed on a Büchner porcelain funnel, using suction. The filtrate we will call "solution A." The precipitate was then dried and ignited in a large porcelain crucible. The resulting metal was dissolved in aqua regia and freed of nitric acid. This solution was diluted and precipitated by potassium iodide, and the filtrate ("solution B") removed as above.

From solutions A and B, separately, the platinum metals were first removed by long boiling with ammonium formate. The metal—1 to 2 grams in weight, mostly palladium—was filtered and the filtrate and washings were examined further for other heavy metals by the usual methods.

Separation of the Palladium from the Platinum Metals.—Considering now the ammonium-formate precipitate, Erdmann and Makowka[1] have obtained satisfactory separations of palladium from platinum and iridium by treating the solution of the mixed chlorides with acetylene. Palladium comes down as acetylide and the other metals are unprecipitated. I found also that rhodium solutions even on heating were not precipitated by acetylene. As for osmium, the ease with which it oxidizes and the high volatility of its oxide makes its elimination, in the process of preparing the palladium, fairly certain. Ruthenium, the rarest element among the platinum metals, need hardly be looked for; still it was sought for in the iridium found. The acetylene method was used, for lack of a safer one, though very tedious. In solutions at all concentrated, I find the palladium ceases to precipitate long before it is entirely removed from solution. Perhaps this is due to the accumulation of acid liberated in the process. At least, when the solution is separated from the acetylide, evaporated and diluted again, acetylene brings down another portion. After five or six operations, a residual solution was obtained on which acetylene had no further action. The acetylide was now carefully ignited with a little ammonium nitrate, the metal redissolved, and the whole process repeated. The residual solution was then added to the first and from it NH_4Cl brought down platinum.

In the chlor-platinate no iridium was found. It was ignited, and the metal was entirely soluble in a few drops of aqua regia. It was again precipitated with NH_4Cl and finally weighed as platinum. $Pt = 1.6$ mg. = 0.007 per cent. No rhodium was found in the filtrate. In the attempt to dissolve in aqua regia the several portions of metal formed by igniting the acetylide, tiny insoluble residues accumulated. These were fused with $KHSO_4$, which, as is well known, dissolves palladium and rhodium, but not iridium or platinum if the temperature is kept low. The soluble portion was dissolved in water and precipitated with ammonium formate. It turned out to be palladium, since it was precipitated by potassium iodide and no trace of rhodium was found.

The portion insoluble in $KHSO_4$ was freed from silica (which came from the dish) by $HCl + HF$, and was then ignited and weighed. $Ir + Ru$ (?) = 1.9 mg. = 0.008 per cent. When fused with $K_2CO_3 + KNO_3$, some blue insoluble IrO_3 was formed, but the fusion showed no yellow color, and in view of the minute quantity of material, it was not thought worth while to search more carefully for ruthenium.

[1] Zeitschr. anal. Chemie, 46, 145-150, 1907.

The final precipitate of palladium acetylide was changed to chloride, diluted, and saturated with SO_2 for gold, but none appeared.

Nothing else was found in the metal except a trace of copper. The iron found earlier had to be reprecipitated several times from chloride solution by ammonia to get rid of palladium. The precipitate was finally transformed into sulphate and determined volumetrically. $Fe = 2.6$ mg. $= 0.010$ per cent.

ANALYSIS OF PALLADIUM.

Au	None
Ru	None
Rh	None
Pt	.007
Ir	.008
Cu	Trace
Zn	Doubtful trace
Fe	.010

0.025 per cent.

In the following table, the results of these analyses of metals for the temperature scale are summarized:

SUMMARIZED ANALYSES OF METALS.[1]

Impurities stated in fractions of 1 p. ct.	Palladium.	Cobalt.	Nickel.	Copper.	Silver.	Aluminum.	Antimony.	Zinc.	Cadmium.
Pt	0.007	none	.0023	[2].0011	.0001				
Ir	.008								
Rh	none								
Ru	none								
Au	none	none	none	none	.0005				
Se				none					
Te				none					
As		none	none	none	none	none	none	none	none
Sb		none	none	none	none	none		.002	
Sn		none	none	none	none		.02(?)		
Hg					none		none		
Ag		none	none	.0006			none	none	
Pb	none	.0176	.0001	none	.0008		trace?	.051	.0860
Bi	none	none	none	none	none		none	none	
Cu	trace	.0178	.0523		trace	.003	.004	none	trace
Cd	none	none	none	none	none		none	.004	
Ni	none	none		none	none	none	none	none	none
Co	none		.1063	none	none	none	none	none	none
Fe	.010	.0006	.0042	.0038	.0011	.043	.007	.006	.0025
Zn	trace?	none?	none?	.0007	none?	none	none		trace
Mn		none	none				none		
Si				none		.190		none	
C					.0003	.013			
S		.013	none	.0020	.0004	.002	trace?	none	.0005
P						none			
Ca						none			
Na						none			
K						none			
Total	.025	.049	.165	.008	.003	.251	.031	.063	.089

[1] A blank opposite any impurity means that it was not looked for.   [2] Means platinum metals.

16. THE FIXED POINTS.

FURTHER DETAILS ON THE SUBSTANCES EMPLOYED FOR THE TEMPERATURE CONSTANTS.

Zinc.—Two samples of "C. P. sticks" were used, both from Eimer and Amend. No appreciable difference could be observed between their melting-points. Both melting and freezing points were sharp and measurable to a fraction of a microvolt. Successive readings did not differ by more than one microvolt. The charge was about 200 grams.

Antimony.—Two samples of metal were used, both from Kahlbaum, and no appreciable difference was found between their melting-points. The charge weighed about 150 grams. The melting-point is sharp and does not differ from the freezing-point by more than one microvolt, provided the undercooling which always precedes solidification does not exceed 15°. If the metal is undercooled too far to give an accurate freezing-point, the fact is easily recognized by observing that the thermo-element does not return to a sustained constant temperature, but merely rises to a maximum, then falls again. The amount of undercooling is greater the higher the metal has been heated above its melting-point after the melting is complete.

Silver.—The charge weighed about 260 gms. Only one supply was used. The melting and freezing points were sharp and agreed within one microvolt.

Gold.—A new charge of gold was used, weighing 350 grams. This was obtained from Dr. Eckfeldt of the Philadelphia Mint.

Copper.—The copper was obtained in the form known as "copper drops cooled in hydrogen" (Eimer and Amend). Only one supply was used. The melting and freezing points were not quite as sharp as was the case with silver, but always agreed within 1 microvolt. The temperature is very susceptible to a trace of oxide, which not only lowers the temperature appreciably, but makes it more uncertain, so that if a little oxidation has taken place it is recognizable at once. Waidner and Burgess[1] found that the best commercial electrolytic copper showed an average difference of 0.2° in the melting-point from the purified copper drops. Charge, about 210 grams.

Diopside (*Magnesium-calcium metasilicate*, $MgSiO_3$. $CaSiO_3$).—Two samples of chemically pure, artificial diopside were used, one from the preparation of Allen and White[2] and the other made up in 1909 by G. A. Rankin. No appreciable difference was found between the melting-points. No freezing-point can be obtained, as the mineral undercools considerably. The charge used was 3 grams.

Nickel.—A sample of specially purified electrolytic nickel was obtained from Kahlbaum. The analysis showed less than 0.2 per cent total impurities. Care must be taken in the case of nickel that no oxide forms, as a fairly sharp break can be observed about 10° below the melting-point, which may represent the eutectic of nickel and nickel oxide. This break disappeared when the nitrogen was replaced for a few minutes by hydrogen. This lower point might easily be mistaken for the melting-point of the metal, and this mistake may possibly have occurred in several of the published determinations of the melting-point of nickel. Nickel absorbs hydrogen and possibly also nitrogen, and after cooling frequently showed excrescences and signs of "spitting" such as occur with silver in air.

[1] Phys. Rev. 28, p. 469, 1909. Bull. Bur. Stds., 6, p. 174, 1909.   [2] Am. Jour. Sci., (4), 27, 1-47, 1909.

Cobalt.—Kahlbaum's purest cobalt was used, containing less than 0.05 per cent total impurity. It was in the form of fine black powder, which was compressed into blocks for convenience in handling. The results obtained were not quite as satisfactory as with nickel on account of the higher temperature and more rapid contamination of the thermo-element. The absorption of gases seemed to be less than was the case with nickel.

Samples of Eimer and Amend's "98 to 99 per cent pure" nickel and cobalt were also tried. The difference between the two samples of nickel was not greater than the uncertainty in the melting-point caused by contamination of the thermo-element. The "98 to 99 per cent pure" cobalt melted about 3.5° lower than the pure sample. Since the impurities in nickel are usually chiefly iron and cobalt, and those of cobalt are chiefly iron and nickel, and since the melting-points of all three are close together, the melting-points of the slightly impure metals can not be expected to lie far from those of the pure metals.

Anorthite (Aluminum-calcium silicate, $CaAl_2 Si_2O_8$, or $Al_2SiO_5.CaSiO_3$).— The anorthite used was made from pure analyzed materials by G. A. Rankin in 1909. The charge was about 3 grams. The melting-point is not quite as sharp as that of diopside. Only the melting-point can be obtained, as the mineral undercools considerably; it may even cool to glass without crystallization, in which case of course no melting-point will be obtained on the following heating.

Palladium.—About 350 grams of pure palladium, in the form of sheet, was loaned to us by Dr. Heraeus. It melts and freezes quite sharply, making an excellent substance for a fixed thermometric point. The greatest uncertainty is caused by the vaporization of the metal and consequent contamination of the thermo-element wire. The charges used weighed 128 and 210 grams respectively.

Cadmium and Aluminum.—In addition to the fixed points just described, two other metal melting-points, cadmium and aluminum, were incidentally determined. Only one measurement of the cadmium point was made on the gas thermometer, and this chiefly for the purpose of checking the extrapolation below the zinc point. The conditions of melting were the same as for zinc. The charge weighed 215 grams.

A sample of pure aluminum obtained from the Aluminum Company of America was melted in a graphite crucible of the usual size in an atmosphere of carbon monoxide. On account of the sensitiveness of aluminum to silicon contamination, the tube carrying the thermo-element was provided with a thin protecting cover of graphite, so that the metal came in contact only with pure graphite. The freezing-point was sharp and constant. The melting-point was less sharp, but lay within 0.5° of the freezing-point.

MELTING-POINT MEASUREMENTS.

Table XIV contains in summarized form the readings of the various thermo-elements at the melting-points of the standard substances. The values are in microvolts, on the basis: Clark cell at 15°= 1.4328 volts. Each value given represents from one to six determinations of the melting and freezing points (in the case of aluminum, diopside, and anorthite, melting-points only). The thermo-element readings are given at the constant temperatures chosen to be the reference points of the nitrogen scale. Each

element is represented by a letter (or a number in parenthesis). Thus, element C, after comparison with the gas thermometer in Table XIII, was used to determine the fixed points in Table XIV, after which it was returned to the gas-thermometer furnace for further comparison. "A" in copper read 10505 in Dec. (1908), 10502 in Jan. (1909), 10499 in Feb., 10504 in March, 10503 in May, and 10503 in June.

TABLE XIV.—THERMO-ELEMENT READINGS AT MELTING-POINTS.

Date.	Zinc.	Antimony.	Silver.	Gold.	Copper.	Diopside.
1908						
March	S 3408		S 9056		S 10476	
	V 3401		V 9050		V 10477	
	W 3406		W 9057		X 10485	
	X 3406		X 9058		Y 10577	
	Y 3437		Y 9147		Z 10438	
	Z 3382		Z 9019		V 10478	
			(42) 9066			
			(32) 9081			
April		X 5501			W 10478	
		W 5499			X 10488	
		S 5503			(42) 10489	
		X 5505			(31) 10529	
		Y 5545				
		Z 5466				
June					A 10500	
December	S 3418	S 5506	S 9069		S 10481	
	X 3411	X 5504	X 9071		X 10484	
	Y 3437	Y 5547	Y 9151		Y 10581	
	A 3412	A 5507	A 9087		A 10505	
	(31) 3426					
	(42) 3406					
1909						
January					Y 10573	
					Z 10426	
					A 10502	
					C 10458	
February	Y 3434	Y 5541	Y 9141	Z 10193	Y 10573	
	Z 3382	Z 5459	Z 9022	A 10260	Z 10432	
	A 3409.5	A 5501	A 9080	C 10226	A 10499	
	C 3404	C 5489	C 9049	D 10231	C 10460	
	D 3403	D 5488	D 9055		D 10467	
March	A 3413.5	Z 5462.5	Z 9019	Z 10195	Z 10432	
	C 3409.5	A 5505.5	A 9085	A 10266	A 10504	
	D 3409	C 5495	C 9057	C 10233	C 10469	
		D 5495.5	D 9059	D 10235	D 10473	
					C 10470	
					D 10475	
May					Y 10571	
					Z 10433	
					A 10503	
					D 10469	
					E 10534	
					F 10533	
					G 10531	
					C 10454	
June	Z 5461	Y 9137	Z 10195	Y 10568	E 14230	
	A 5504	Z 9018	A 10263	Z 10432	E 14226	
	E 5530	A 9082	D 10234	A 10503	F 14229	
	F 5530	C 9057	E 10295	D 10470	G 14229	
	G 5529.5	E 9113	F 10296	E 10534	H 14231	
		F 9113	G 10294	F 10534	A 14200	
		G 9111		G 10533		

TABLE XIV.—CONTINUED.

Nickel.	Cobalt.	Palladium.	Anorthite.	Miscellaneous.
(Apr. 1909)	(Sept. 1909)	(Nov. 1909)	(Nov. 1909)	Cd (Mar. 1909)
A 14947	E 15404¹	H 16145	E 16144	Z 2465
D 14883	E 15387¹	J 16144	E 16151	C 2488
Z 14850	(Oct. 1909)	J 16158	H 16145	D 2486
A 14943	E 15391¹	J 16151	F 16141	Cd (Mar. 1910)
D 14881	E 15439	E 16143	G 16148	E 2502
Z 14847	F 15435	F 16138	C 16060	
Z 14853	G 15441	G 16145		Al (Mar. 1908)
E 14974	H 15436	C 16058		Z 5758
F 14975	J 15445	(Jan. 1910)		Z 5757
G 14975	C 15359	J 16150		V 5793
H 14977	A 15409	J 16140		Y 5836
(Sept. 1909)		(Apr. 1911)		
E 14980		L 16145		NiO-Ni(Apr. 1908)
F 14981		(Wire method)		Z 14723
G 14981				S 14750
H 14983				S 14743
				V 14747
				NiO-Ni (Apr. 1909)
				Z 14712
				Z 14717

¹Commercial metal.

TEMPERATURE OF THE FIXED POINTS.

Table XV contains the final temperature of each thermometric point studied. In the first column is the number of the experiment corresponding to that in Table XIII. In the second column is the correction in degrees to be applied to each of the thermo-element readings *outside* of the bulb, integrated from the readings of the auxiliary elements as described on page 66; in the third column is given the corresponding correction in microvolts. In the fourth column are the readings of the standard elements on the *outside* of the bulb, corrected as above mentioned. In the fifth column are the readings of the same thermo-elements at the fixed point in question, as obtained in the melting or freezing of metal or salt; these figures usually represent the mean of a considerable number of determinations.

In the sixth and seventh columns are the corresponding figures for the element *inside* of the bulb. In this case, however, no correction has been applied to the reading of the element, since, being located practically at the center of the bulb, it might be expected to represent the mean temperature of the entire volume of the bulb.

In the eighth and ninth columns are the temperatures of the fixed points derived from the preceding four columns. In the last column is given the weight assigned to each measurement. In assigning these weights the number of standard thermo-elements used, the amount of variation in p_0, and other incidental variables were taken into consideration.

As has been pointed out on page 65, the relative weights to be assigned to the inside and outside elements are different at different temperatures:

TABLE XV.—TEMPERATURES OF THE FIXED POINTS—Continued.

Silver Point. 960.0°

Exp. No.	Integrated correction to outside elements.		Standard elements.				Temperature.		Weight.
	Degrees.	M. V.	Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	By outside element.	By inside element.	
6	+0.8	+9	W 9070	9057	X 9100	9071	959.4°	958.0°	1
26	−0.3	−3	A 9087	9083	Y 9159	9141	959.9	958.6	2
27	−0.8	−9	A 9066	9083	Y 9119	9141	959.9	960.4	2
35	−0.7	−8	A 9079	9082	Y 9142	9141	959.7	959.4	1
36	−0.1	−1	A 9097	9082	Y 9163	9141	959.4	958.7	1
41	−0.3	−3	A 9083	9081	Y 9156	9141	959.6	958.5	2
42	−0.8	−9	A 9076	9081	Y 9131	9141	959.3	959.7	2
63	−0.6	−7	A 9079	9084			960.7		
			D 9048	9058	Z 9010	9019	961.2		
							960.9	961.1	2
68	−0.7	−8	A 9080	9085			960.3		
			D 9051	9058	Z 9013	9019	960.4		
							960.4	960.3	2
76	−0.2	−2	A 9088	9082			959.2		
			E 9112	9113			959.7		
			F 9097	9113			961.2		
			G 9106	9111	Z 9002	9018	960.2		
							960.1	961.2	4
81	+0.3	+3	F 9132	9113			959.5		
			E 9131	9113			959.6		
			A 9083	9082			961.1		
			G 9125	9111	Z 9015	9018	960.0		
							960.0	961.5	4
88	+0.3	+3	F 9143	9113			959.0		
			E 9139	9113			959.4		
			A 9093	9082			960.7		
			G 9135	9111	Z 9036	9018	959.6		
							959.7	960.1	4
					Weighted mean,		959.9°	960.2°	

Gold Point. 1062.4°

64	−0.3	−3	A 10262	10265			1062.4°		
			D 10226	10233	Z 10178	10193	1062.8		
							1062.6	1063.4°	2
69	−0.4	−4	A 10253	10266			1061.4		
			D 10217	10234	Z 10169	10193	1061.7		
							1061.6	1062.3	2
77	−0.3	−3	A 10255	10263			1061.2		
			E 10282	10295			1061.6		
			F 10263	10296			1063.4		
			G 10276	10294	Z 10161	10193	1062.1		
							1062.1	1063.3	4

TABLE XV.—TEMPERATURES OF THE FIXED POINTS—Continued.

Gold Point. 1062.4°—Continued.

Exp. No.	Integrated correction to outside elements. Degrees.	M. V.	Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	By outside element.	By inside element.	Weight.
82	+0.4	+4	F 10303	10296	....	....	1061.9°		
			E 10304	10295	....	....	1061.8		
			A 10256	10263	....	....	1063.1		
			G 10296	10294	Z 10181	10193	1062.4		
							1062.3	1063.6°	4
					Weighted mean,		1062.2°	1063.2°	

Copper Point. 1082.6° (*Lower Pressure.* $p_0 = 217$–221 mm.)

Exp. No.	Degrees.	M. V.	Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	By outside element.	By inside element.	Weight.
2	+1.2	+14	W 10457	10478	X 10491	....	1081.7°	....	1
9	+1.0	+12	W 10495	10478	X 10555	....	1082.2	....	1
11	+1.2	+14	W 10487	10478	X 10512	....	1083.1	....	1
18	+0.7	+ 8	A 10510	10502	Y 10612	10573	1082.2	....	2
19	—0.4	— 5	A 10501	10502	Y 10584	10573	1082.0	1081.0°	3
20	—0.8	— 9	A 10488	10502	Y 10555	10573	1082.1	1082.5	3
28	—0.3	— 4	A 10512	10501	Y 10593	10573	1082.1	1081.4	3
29	—0.9	—10	A 10494	10501	Y 10556	10573	1082.2	1083.0	3
37	—0.6	— 7	A 10504	10501	Y 10576	10573	1082.0	1082.0	2
38	—0.3	— 4	A 10509	10500	Y 10585	10573	1082.2	1081.9	2
39	+0.7	+ 8	A 10517	10500	Y 10617	....	1082.3	....	2
43	—0.3	— 4	A 10512	10500	Y 10595	10573	1082.2	1081.3	3
44	—0.9	—10	A 10501	10499	Y 10568	10573	1082.0	1082.6	3
45	+0.6	+ 7	A 10515	10499	Y 10617	....	1082.3	....	2
89	+0.5	+ 6	F 10546	10534	....	....	1081.8		
			E 10544	10534	....	....	1081.9		
			A 10496	10503	....	....	1083.4		
			G 10538	10533	Z 10428	10432	1082.4		
							1082.4	1083.1	4
126[1]	+0.4	+ 5	E 10631	10534	....	....	1082.2		
			F 10627	10534	....	....	1082.6		
			G 10621	10533	....	....	1083.0		
			H 10623	10535	C 10567	10470	1083.0		
							1082.7	1082.5	4
					Weighted mean,		1082.2°	1082.2°	

Copper Point—(*Higher Pressure.* $p_0 = 346$–347 mm.)

Exp. No.	Degrees.	M. V.	Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	By outside element.	By inside element.	Weight.
60	—0.7	— 8	A 10500	10502	....	....	1083.4°		
			D 10465	10470	Z 10422	10432	1083.6		
							1083.5	1084.1°	1
65	—0.8	—9	A 10502	10503	....	....	1083.0		
			D 10465	10471	Z 10420	10432	1083.4		
							1083.2	1083.9	2
70	—0.3	—4	A 10508	10504	....	....	1082.4		
			D 10475	10472	Z 10444	10432	1082.6		
							1082.5	1081.8	2

[1]Made with outside-wound furnace. See page 56 and *Fig.* 10.

TABLE XV.—TEMPERATURES OF THE FIXED POINTS—Continued.

Silver Point. 960.0°

| Exp. No. | Integrated correction to outside elements. | | Standard elements. | | | | Temperature. | | Weight. |
	Degrees.	M. V.	Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	By outside element.	By inside element.	
6	+0.8	+9	W 9070	9057	X 9100	9071	959.4°	958.0°	1
26	−0.3	−3	A 9087	9083	Y 9159	9141	959.9	958.6	2
27	−0.8	−9	A 9066	9083	Y 9119	9141	959.9	960.4	2
35	−0.7	−8	A 9079	9082	Y 9142	9141	959.7	959.4	1
36	−0.1	−1	A 9097	9082	Y 9163	9141	959.4	958.7	1
41	−0.3	−3	A 9083	9081	Y 9156	9141	959.6	958.5	2
42	−0.8	−9	A 9076	9081	Y 9131	9141	959.3	959.7	2
63	−0.6	−7	A 9079	9084	....		960.7		
			D 9048	9058	Z 9010	9019	961.2		
							960.9	961.1	2
68	−0.7	−8	A 9080	9085	....		960.3		
			D 9051	9058	Z 9013	9019	960.4		
							960.4	960.3	2
76	−0.2	−2	A 9088	9082	....		959.2		
			E 9112	9113	....		959.7		
			F 9097	9113	....		961.2		
			G 9106	9111	Z 9002	9018	960.2		
							960.1	961.2	4
81	+0.3	+3	F 9132	9113	....		959.5		
			E 9131	9113	....		959.6		
			A 9083	9082	....		961.1		
			G 9125	9111	Z 9015	9018	960.0		
							960.0	961.5	4
88	+0.3	+3	F 9143	9113	....		959.0		
			E 9139	9113	....		959.4		
			A 9093	9082	....		960.7		
			G 9135	9111	Z 9036	9018	959.6		
							959.7	960.1	4
				Weighted mean,			959.9°	960.2°	

Gold Point. 1062.4°

64	−0.3	−3	A 10262	10265	....		1062.4°		
			D 10226	10233	Z 10178	10193	1062.8		
							1062.6	1063.4°	2
69	−0.4	−4	A 10253	10266	....		1061.4		
			D 10217	10234	Z 10169	10193	1061.7		
							1061.6	1062.3	2
77	−0.3	−3	A 10255	10263	....		1061.2		
			E 10282	10295	....		1061.6		
			F 10263	10296	....		1063.4		
			G 10276	10294	Z 10161	10193	1062.1		
							1062.1	1063.3	4

TABLE XV.—TEMPERATURES OF THE FIXED POINTS—Continued.

Diopside Point. 1391.2°—Continued.

Exp. No.	Integrated correction to outside elements. Degrees.	M. V.	Standard elements. Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	Temperature. By outside element.	By inside element.	Weight.
103	−0.4	− 5	E 14211	14228	....		1392.5°		
			F 14204	14229	....		1393.1		
			G 14217	14229	....		1392.1		
			H 14230	14231	Z 14124	14103	1391.2		
							1392.2	1389.4°	3
104	+1.0	+13	E 14242	14228	....		1392.5		
			F 14212	14229	....		1394.9		
			G 14249	14229	....		1392.0		
			H 14262	14231	Z 14155	14103	1391.1		
							1392.6	1389.3	3
106	−0.6	− 8	E 14228	14228	....		1391.7		
			F 14225	14229	....		1392.0		
			G 14233	14229	....		1391.3		
			H 14243	14231	Z 14123	14103	1390.7	1390.0	2
							1391.4		
107	+0.9	+12	E 14248	14228	....		1391.9		
			F 14237	14229	....		1392.8		
			G 14245	14229	....		1392.2		
			H 14252	14231	Z 14152	14103	1391.8	1389.4	2
							1392.2		
130	−0.6	− 7	E 14243	14228	....		1390.2		
			F 14241	14230	....		1390.6		
			G 14249	14230	....		1389.9		
			H 14239	14228	C 14146	14153	1390.6		
							1390.3	1392.0	3
					Weighted mean,		1392.0°	1390.4°	

Nickel Point. 1452.3°

Exp. No.	Integrated correction to outside elements. Degrees.	M. V.	Standard elements. Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	Temperature. By outside element.	By inside element.	Weight.
109	+0.7	+ 8	E 15028	14977	....		1451.2°		
			H 15027	14980	Z 14903	14850	1451.6		
							1451.4	1451.1°	1
111	0	0	E 14980	14977	....		1453.2		
			H 14978	14980	Z 14867	14850	1453.7		
							1453.5	1452.1	2
112	+0.9	+11	E 14971	14977	....		1453.8		
			F 14958	14978	....		1454.9		
			H 14991	14980	Z 14872	14850	1452.4		
							1453.7	1451.5	

TABLE XV.—TEMPERATURES OF THE FIXED POINTS—Continued.

Nickel Point. 1452.3°—Continued.

Exp. No.	Integrated correction to outside elements.		Standard elements.				Temperature.		Weight.
	Degrees.	M. V.	Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	By outside element.	By inside element.	
123	−0.6	− 7	E 14984	14977	....	....	1454.3°		
			F 14989	14978	A 14982	14945	1453.9		
							1454.1	1451.8°	2
124	+0.8	+10	E 14989	14977	....	....	1454.6		
			F 14994	14978	A 14996	14945	1454.3		
							1454.5	1451.5	1
133	−0.3	− 4	E 14954	14977	....	....	1451.9		
			F 14958	14976	....	....	1451.5		
			G 14955	14981	....	....	1452.2		
			H 14946	14977	C 14882	14898	1452.5		
							1452.0	1451.3	4
					Weighted mean,		1453.0°	1451.6°	

Cobalt Point. 1489.8°

115	+0.1	+ 1	E 15390	15439	....	....	1488.7°		
			F 15375	15435	A 15357	15409	1489.6		
							1489.1	1488.9°	3
116	+1.4	+17	E 15428	15439	....	....	1490.5		
			F 15434	15435	....	....	1489.7		
			G 15435	15441	A 15421	15409	1490.1		
							1490.1	1488.6	3
118	−0.5	− 6	E 15385	15439	....	....	1491.7		
			F 15383	15435	....	....	1491.6		
			G 15393	15441	A 15382	15409	1491.3		
							1491.5	1489.6	2
120	−0.4	− 5	E 15381	15439	....	....	1491.7		
			F 15371	15435	....	....	1492.1		
			G 15363	15441	A 15379	15409	1493.3		
							1492.7	1489.4	1
121	+0.7	+ 9	E 15406	15439	....	....	1492.0		
			F 15405	15435	....	....	1491.8		
			G 15398	15441	A 15412	15409	1492.8		
							1492.2	1489.1	1
					Weighted mean,		1490.6°	1489.0°	

Palladium Point. 1549.2°

134	−0.7	− 9	E 16151	16143	....	....	1549.5°		
			F 16161	16138	....	....	1548.3		
			G 16139	16145	....	....	1550.6		
			H 16147	16145	C 16075	16058	1550.1		
							1549.6°	1548.8°	

TABLE XV.—TEMPERATURES OF THE FIXED POINTS—Continued.

Anorthite Point. 1549.5°.

Exp. No.	Integrated correction to outside elements. Degrees.	M. V.	Standard elements. Outside corrected.	Fixed point.	Inside uncorrected.	Fixed point.	Temperature. By outside element.	By inside element.	Weight.
134	−0.7	−9	E 16151	16148	....		1549.9°		
			F 16161	16141	....		1548.6		
			G 16139	16148	....		1550.9		
			H 16147	16145	C 16075	16060	1550.0		
							1549.9°	1549.0°	

Interpolation Points.

49	−0.1	−1	A 2486	2492	....		320.2°		
			D 2482	2486	Z 2462	2465	320.0		
							320.1°	319.9°	
					Mean for cadmium,		320.0°		
51	0.0	0	A 4451	4450	....		524.6		
			D 4439	4442	Z 4413	4417	525.0		
							524.8°	525.1	
					Mean for A = 4450,		524.9°		
62	0.0	0	A 7895	7900	....		854.2		
			D 7869	7881	Z 7829	7848	854.9		
							854.6°	855.5	
67	−0.2	−2	A 7883	7900	....		854.0		
			D 7859	7881	Z 7820	7848	854.5		
							854.3°	855.0	
					Mean for A = 7900,		854.7°		
128	−0.2	−2	E 12004	12000	....		1206.3		
			F 12001	12001	....		1206.7		
			G 12008	12001	....		1206.1		
			H 12000	12003	C 11914	11928	1206.9		
							1206.5°	1207.8	
132	+0.1	+1	E 11947	12000	....		1206.0		
			F 11952	11997	....		1205.3		
			G 11950	12001	....		1205.8		
			H 11941	12003	C 11887	11928	1206.8		
							1206.0°	1205.0	
					Mean for E = 12000,		1206.4°		
129	−0.6	−5	E 13107	13100	....		1297.4		
			F 13102	13101	....		1297.9		
			G 13110	13101	....		1297.2		
			H 13101	13103	C 13007	13023	1298.1		
							1297.7°	1299.3	
					Mean for E = 13100,		1298.5°		

17. INTERPOLATION BETWEEN THE FIXED POINTS.

The preparation of formulæ to represent the relation between the temperature defined by the gas thermometer and the electromotive force of a thermo-element has always been a cause of considerable dissatisfaction, both to the maker and the user. The chief reason for this is perhaps the fact that the formulæ used have been applicable only to limited portions of the curve and have therefore given no suggestion of physical significance. In the Reichsanstalt publication[1] the data extended from 300° to 1100° and included several good fixed points (melting-points of pure metals) between which no interpolation, however rough, could go far astray. Accordingly, in so far as interpolation was concerned, but little attention required to be given to the formulation of this relation. It was sufficient that a simple formula of the form

$$e = -a + bt + ct^2$$

could be made to represent the observations between 300° and 1100° within the limits of errors of observation.

If the investigator's responsibility could be made to end with the representation of his own observations, no serious difficulty would arise, but such a formula when published is placed in the hands of many who do not realize that no physical significance was attached to the formula by its author and that its extrapolation in either direction would be fraught with grave danger. A mere inspection of the equation is sufficient to show that the electromotive force does not become zero for zero temperature, thereby immediately proving that extrapolation downward does not correspond to the observed readings of the thermo-element. In the Reichsanstalt equation this constant term was in fact sufficiently large to lead to absurdities if the extrapolation was continued far below 300°.

Notwithstanding the warning contained in this situation, extrapolation upward of the thermo-electric curve has been employed almost universally for the determination of temperatures above 1100°, not only for direct determinations of temperature with the thermo-element itself, but also for the calibration of optical pyrometric apparatus. The absence of absolute determinations in this region has left this practice in undisturbed security until recently, when some doubt has been thrown upon the validity of irresponsible upward extrapolation by various observations:

(1) The increase in the accuracy now attainable with the optical pyrometer has given an independent thermal scale comparable with that of the thermo-element and overlapping the same region. The two curves have not been found to correspond.

(2) Experimental determinations of the melting-point of platinum by continuing observations of the thermo-element up to a point where a portion of its platinum wire melts, have been undertaken in the national laboratories of Germany, England, and the United States, and have yielded a value measured upon the extrapolated thermo-electric curve of about 1710°. The agreement in the different determinations was good and the result found general acceptance for a time. More recently, as has been stated,

[1] Holborn and Day, 1900, loc. cit.

Holborn and Valentiner have made successful measurements with the gas thermometer at the temperature of melting palladium, and although high accuracy was not attempted, it became clear that the palladium point obtained by extrapolating with the thermo-element was much too low and by inference the platinum point even more so, for the various optical methods give opportunity for a very good determination of the temperature difference between the melting-points of the two metals. The most recent estimates of the platinum melting-point obtained in this way have placed it between 1750° and 1755°, indicating that the upward extrapolation with the thermo-element has given rise to an error of about 45° at the platinum point (see following table.)

The data obtained in the present investigation throw much light upon this situation. If we take the observations of our series over the range covered by the Reichsanstalt scale (300° to 1100°) and write an equation for these of the same type as that used at the Reichsanstalt, it will read

$$e = -302 + 8.2356t + .0016393t^2$$

and this equation will reproduce the temperatures of the standard melting-points which fall in this region with a maximum error of 3 microvolts (=0.3°), an accuracy far within the errors of observation. But if we extrapolate this curve in accordance with the general practice above described, and compare the resulting electromotive forces with our observations between 1100° and the melting-point of platinum, a somewhat startling surprise awaits us. Although the curve below the copper point is a practically perfect reproduction of the observations, it diverges from the gas-thermometer scale at the melting-point of palladium by 248 microvolts, which represents a temperature error of 20°. At the platinum melting-point it has grown to 45°. This comparison is made in the table below.

	Temp.	Observed.	Calculated.	Observed–Calculated	Observed–Calculated.
	°	mv.	mv.	mv.	°
Zinc	418.2	3429	3429	0	0.0
Antimony	629.2	5530	5530	0	0.0
Silver	960.0	9113	9115	−2	−0.2
Gold	1062.4	10295	10298	−3	−0.3
Copper	1082.6	10534	10534	0	0.0
			Extrapolation.		
	1206.4	12000	12019	− 19	− 1.6
	1298.5	13100	13156	− 56	− 4.7
Diopside	1391.2	14228	14328	−100	− 8.3
Nickel	1452.3	14977	15116	−139	−11.5
Cobalt	1489.8	15439	15606	−167	−13.8
Palladium	1549.2	16143	16391	−248	−20.6
Platinum	(1752.)[1]	18616	19159	−543	−45.3

If, on the other hand, we represent t as a function of e, using the same data as before, the equation will take the form

$$t = 47.2 + 0.11297e - 1.3946 \ (10)^{-6}e^2$$

[1] Values in parenthesis extrapolated (see p. 113).

This curve passes through the fixed points below 1100°, nearly as accurately as the previous one, and is also quite competent to interpolate temperatures through the range of the old standard scale. Extrapolating this in turn up to the platinum point and comparing it with our gas-thermometer measurements in the higher region leads to temperatures about 42° too low for palladium and 85° too low for platinum.

	Observed.	Calculated.	Observed—Calculated.
	°	°	°
Zinc...............	418.2	418.2	0.0
Antimony.........	629.2	629.3	—0.1
Silver............:	960.0	960.9	—0.9
Gold.............	1062.4	1062.4	0
Copper..........	1082.6	1082.5	+0.1

Extrapolation.

	1206.4	1202.0	+ 4.4
	1298.5	1287.8	+10.7
Diopside..........	1391.2	1372.2	+19.0
Nickel...........	1452.3	1426.3	+26.0
Cobalt...........	1489.8	1458.9	+30.9
Palladium........	1549.2	1507.4	+41.8
Platinum.........	(1752.)	1667.	+85.

The untrustworthiness of the present practice of extending thermo-element values obtained below 1100° into the region above that temperature is therefore abundantly demonstrated.

We were unable to find a simple parabola with which to represent the whole series of observations between 300° and 1550° within the errors of observation. The simplest procedure is therefore to divide the long curve into two parts. This plan is carried out below in the form in which it will probably be found most useful. A parabola passing through zinc, antimony and copper reproduces the results over that temperature range within the errors of observation. A similar parabola through copper, diopside, and palladium gives the upper temperatures as accurately as they were measured. These two equations offer a means of safe and convenient interpolation throughout the entire range of gas-thermometer measurements. In this series are included certain gas-thermometer measurements given at the end of Table XV, which were made at temperatures between the fixed melting-points, for the purpose of checking the interpolation formula, together with a single gas-thermometer determination of the cadmium melting-point and the extrapolated platinum point described on p. 115. The temperature 854.1 appears here corrected by —0.6°, since the series, of which this measurement formed a part, showed a systematic difference of about this amount from the final average of antimony and silver, which lie on either side of this point.

CADMIUM TO COPPER. $e = -302 + 8.2356t + .0016393t^2$

	Temperature.	Observed.	Calculated.	Observed—Calculated	Observed—Calculated.
	°	mv.	mv.	mv.	°
Cadmium.......	320.0	2502	2501	+1	+0.1
Zinc...........	418.2	3429	3429	0	0.0
	524.9	4470	4472	−2	−0.2
Antimony......	629.2	5530	5530	0	0.0
	854.1	7929	7928	+1	+0.1
Silver.........	960.0	9113	9115	−2	−0.2
Gold..........	1062.4	10295	10298	−3	−0.3
Copper........	1082.6	10534	10534	0	0.0

COPPER TO PALLADIUM. $e = -1941 + 11.1746t + .0003216t^2$

Copper........	1082.6	10534	10534	0	0.0
	1206.4	12000	12008	− 8	−0.7
	1298.5	13100	13111	−11	−0.9
Diopside.......	1391.2	14228	14228	0	0.0
Nickel.........	1452.3	14977	14967	+10	+0.8
Cobalt.........	1489.8	15439	15421	+18	+1.5
Palladium......	1549.2	16143	16143	0	0.0
Platinum.......	(1752.)	18616	18624	− 8	−0.7

It is possible to write a cubic equation which will reproduce the entire series from zinc to palladium without error greater than the normal accuracy of the observations themselves, but even this equation goes astray at the platinum point by 5°, and reminds us again of the absence of physical significance in all these formulæ. The equation offered makes no pretensions to a least-square solution with balanced residuals, but is arranged so that the greatest uncertainties are found in that portion of the curve where the greatest experimental error lies. The coefficients were rounded off for convenience of computation.

CADMIUM TO PALLADIUM. $e = -169 + 7.57t + 0.002648t^2 - 0.0000004724t^3$

	Temp.	Observed.	Calculated.	Observed—Calculated.	Observed—Calculated.
	°	mv.	mv.	mv.	°
Cadmium.......	320.0	2502	2509	− 7	−0.8
Zinc...........	418.2	3429	3425	+ 4	+0.4
	524.9	4470	4466	+ 4	+0.4
Antimony......	629.2	5530	5525	+ 5	+0.5
	854.1	7929	7934	− 5	−0.5
Silver.........	960.0	9113	9121	− 8	−0.7
Gold..........	1062.4	10295	10296	− 1	−0.1
Copper........	1082.6	10534	10530	+ 4	+0.3
	1206.4	12000	11988	+12	+1.0
	1298.5	13100	13091	+ 9	+0.7
Diopside.......	1391.2	14228	14215	+13	+1.1
Nickel.........	1452.3	14977	14963	+14	+1.2
Cobalt.........	1489.8	15439	15424	+15	+1.2
Palladium......	1549.2	16143	16157	−14	−1.2
Platinum.......	1752.	18616	18681	−65	−5.4

18. EXTRAPOLATION UPWARD. MELTING-POINT OF PLATINUM.

Now that the gas thermometer has given us measured temperatures up to 1550°, the extrapolation out to the platinum melting-point, which in recent years has been variously estimated at from 1710° (Harker) to 1855° (Barus), should at least become more certain than heretofore. To extrapolate 200° beyond the upper limit of a curve which has been measured from 300° to 1550° is a task of quite different character from the one hitherto undertaken of extrapolating 650° beyond a measured curve which stopped at 1100°.

Two methods are available and convenient for making this extrapolation:

(1) To continue observations of the electromotive force of the thermo-element until the platinum wire melts.

(2) To employ one of the radiation pyrometers to measure the temperature interval from palladium to platinum.

The first method is the most sensitive one available in this temperature region and inasmuch as we had been using it continuously and successfully for purposes of interpolation, the opportunity seemed favorable for adding as good an estimate of this classical temperature point as the rather unusual facilities at our disposal permitted. Platinum, like gold, offers an ideal fixed temperature during melting. The melting-point is sharp, it can be determined in air without fear of oxidation or contamination either from the atmosphere or from contact with lime, magnesia, or stable silicates. Moreover, the purity of platinum is so readily checked by its physical properties (electromotive force in thermo-elements, temperature coefficient of conductivity) that there is hardly a possibility of uncertainty from this cause. The present determinations were made by melting the platinum wire of Heraeus thermo-elements of which the recorded electromotive force will afford a sufficient guarantee of its purity. The impurities contained in these wires are hardly determinable quantitatively by chemical means.

Each thermo-element was heated gradually up to the melting-point of the platinum wire, within a glazed Marquardt porcelain tube, in the region of maximum temperature of a resistance furnace of the carbon tube type.[1] Carbon monoxide around the outside of the porcelain tube protected the furnace from oxidation, and a current of dry air in the inside prevented contamination of the thermo-element. Both wires of the element were inclosed in Marquardt capillaries, leaving only about 2 mm. of the platinum exposed next to the junction. It was always this portion that melted, the point being marked by a halt of about one minute in the gradual rise in temperature of the element, preceding the formation of a globule and the interruption of the circuit. New Marquardt tubes were used for each determination. Several elements were examined for contamination after the measurement,[2] and no appreciable amount was found. A vertical section of the furnace is shown in Fig. 14.

In Table XVI are given the experimental results. The values are in microvolts, corrected as before.[3] The silver point, being about half way

[1] S. A. Tucker, Trans. Amer. Electrochem. Soc., 11, 303-306, 1907.
[2] Method described on p. 64.
[3] Page 63.

between 0° and platinum, is included in order to indicate the general course of the interpolation curve.

With these are included the results obtained by other observers with similar 10 per cent rhodium alloys. Harker[1] measured the E. M. F. at the melting-point of the platinum wire in a resistance furnace of refractory oxides. Waidner and Burgess[2] made similar measurements in connection with their optical determination of the melting-point of platinum. Their figures, being in terms of the United States legal volt (Clark at 15°= 1.434)

Fig. 14. Carbon-tube furnace for melting-point of platinum. Scale, 1 : 4.

have been corrected to the true volt (Clark at 15°= 1.4328). Other investigators (Holborn and Henning,[3] Nernst and von Wartenberg,[4] Holborn and Valentiner[5]) have measured the melting-point of platinum in various ways, but without recording the thermo-electric data.

In general, the curves for all the different 10 per cent elements, both our own and those of other observers, are similar in form, and the divergence of each from the mean increases with increasing temperature. In this connection it should be remarked that the E. M. F. at the palladium point (16140 microvolts) obtained by Holborn and Valentiner with an element whose gold point was 10295, agrees almost exactly with a similar element from our series, with a gold point of 10295 and palladium point of 16143. The disagreement between various observers as to the melting-points of these metals is, then, not so much a matter of purity of metals or accuracy of thermo-electric measurements, as it is of the evaluation of these in terms of the nitrogen thermometer.

We have extrapolated the curves of our own elements, on which we have complete data, using for this purpose the portion of the curve from 1100° to 1550°. A parabola passed through the melting-points of copper (1082.6°), diopside (1391.2°), and palladium (1549.2°), gives, in the case of the various 10 per cent elements, values for platinum from 1748° to 1753°; the 1 per

[1] J. A. Harker, Proc. Roy. Soc., 76, A, 235-250, 1905.
[2] C. W. Waidner and G. K. Burgess, Bull. Bur. Standards, vol 3, p. 200, 1907.
[3] L. Holborn and F. Henning, Sitzb. Berl. Akad., 1905, 311-317.
[4] W. Nernst and H. von Wartenberg, Ber. Deut. Phys. Ges., 4, 48-58, 1906.
[5] L. Holborn and S. Valentiner, Ann. Phys. (4), 22, 1-48, 1907.

cent alloy gives 1750°–1755° (low sensitiveness); the 5 per cent, 1752°; and the 15 per cent, 1755°. The mean is 1752°.

TABLE XVI.—THERMAL E. M. F. AT MELTING-POINT OF PLATINUM.

Date.	No. of element.	Rh in alloy wire.	Silver.	Platinum.
Day and Sosman:		*p. ct.*	*mv.*	*mv.*
1910, 19 February .... F		10	9103	18619
24 February ...... F		10	9103	18613
25 February .... Y		10	9139	18695
25 February .... Z		10	9018	18487
8 March .... J		10	9106	18603
1 March .... I_1J		1	1960	3560
15 April........... KJ		5	6495	12444
2 March .... $I_{15}J$		15	10375	22303
4 March.......... $I_{15}J$		15	10375	22310
Harker 1905 .... N. P. L. 3		10	(9084)	18580
Harker 1905 .... T. 15		10	(9100)	18693
Waidner and Burgess, 1907 ... P_2		10	(9024)	18369
Waidner and Burgess, 1907.... P_3		10	(9040)	18556
Waidner and Burgess, 1907.... S_1		10	(8991)	18250

We did not personally undertake any measurements with radiation pyrometers, nor has any one yet had an opportunity to make use of our gas-thermometer temperatures for this purpose, but optical determinations of the *temperature interval* between palladium and platinum may be taken from the older observations without serious error so long as the absolute temperature values are not required. Thus, for example, we find:

TEMPERATURE INTERVAL PALLADIUM TO PLATINUM.

Nernst and von Wartenberg (Berlin)......................... 204°
Holborn and Valentiner (at the Reichsanstalt)................ 207°
Waidner and Burgess (at the Bureau of Standards)............ 207°

Mean... 206°

The mean value of this temperature interval from three good determinations is therefore 206°. Having fixed the palladium point on the nitrogen thermometer at 1549°, if we simply add 206° to this number we obtain a second extrapolated value of the platinum point at 1755°, in excellent agreement with the first.

The comparatively short interval over which extrapolation is now required (1550°–1750°) and the fact that two wholly independent methods yield temperatures for melting platinum which differ but 3°, gives to this extrapolation an appearance of trustworthiness which the earlier estimates have not possessed. The melting temperature of pure platinum may therefore be considered fairly secure at 1752° with an absolute error of perhaps ±5°.

19. THE THERMO–ELEMENT CURVE FROM 0° TO 1755°.

Below 300° the sensitiveness of the platinum-platinrhodium element is very low compared with the platinum resistance thermometer, the copper-constantan thermo-element, or the mercury thermometer. Nevertheless, it is often convenient to use an available element for measurements in the lower range; hence we have in addition determined the course of the thermo-element curve from 0° to 300°.

The melting and boiling points of pure substances determined on the gas thermometer form the basis of this calibration as before. The 0° and 100° points are familiar. In the neighborhood of 200° and 300° the boiling-points of pure naphthalene and benzophenon were used. The only gas-thermometer determinations of these two points since the early and somewhat less accurate measurements by Crafts,[1] namely, those of Jaquerod and Wassmer,[2] differ from the values interpolated by Callendar and Griffiths[3] with the resistance thermometer, by 0.26° at 218° and 0.4° at 305°. The values of Jaquerod and Wassmer, which we have used, are 217.68° for naphthalene and 305.44° for benzophenon, at 760 mm. pressure.[4]

In our work with the gas thermometer, one measurement was made at the melting-point of cadmium, to give an indication of the course of the thermo-element curve in this lower region. Being only a single measurement, this has not as much weight as the higher temperatures, which were measured under varied conditions. The value obtained was 320.0°.

The difference between benzophenon and cadmium, determined with three platinum-platinrhodium thermo-elements, was found to be 14.8°. The benzophenon used was Merck's preparation, which boils 0.2° higher than the purest made by Kahlbaum. The difference between Kahlbaum's benzophenon and cadmium is then 15.0°, which is exactly the difference found by Waidner and Burgess at the Bureau of Standards, using a resistance thermometer.[5] On the basis of the benzophenon value adopted above, this difference makes the cadmium point 320.4°. We have arbitrarily connected the two portions of the temperature scale at this point by taking the mean, 320.2°, for cadmium. Since in this region temperatures can not be coveniently obtained closer than 0.2° with the platinum-platinrhodium element, the values are abundantly accurate for the present purpose.

It should not be overlooked that the value which we have obtained for zinc indicates a lower value for the boiling-point of sulphur than the figure 444.5° now in general use. The four independent gas-thermometer determinations that have been made of the sulphur point, although agreeing unusually well, are not free from the possibility of errors of several tenths of a degree, and this fact, taken together with the variability in the point itself with different experimental conditions, makes it probable that the absolute value given for the sulphur point is still somewhat uncertain.

[1] Bull. Soc. Chim., 39, 277–289, 1883.
[2] Jour. Chim. Phys., 2, 52–78, 1904.
[3] Phil. Trans. Roy. Soc., 182, A, 43–72, 119–157, 1891.
[4] The results of Jaquerod and Wassmer have also been used as the standard since 1904 by the Research Laboratory of Physical Chemistry at the Massachusetts Institute of Technology, in their work on electrical conductivity at high temperatures.
[5] Bull. Bur. Stds., 7, 1–9, 1910.

THERMO-ELEMENTS IN EVERY-DAY PRACTICE.

The summarized temperature scale adopted for present use in this laboratory for the calibration of thermo-elements is therefore as follows:

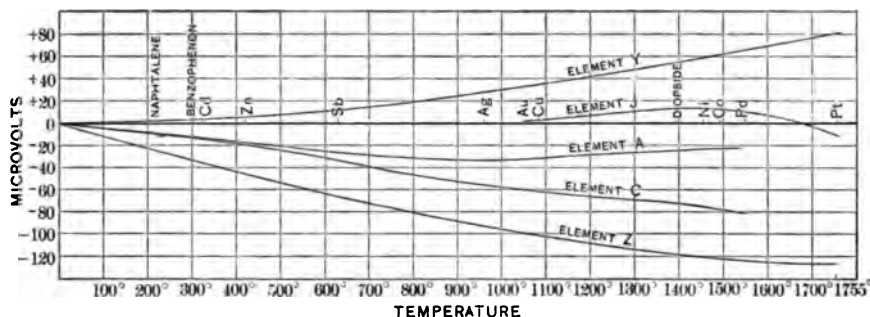|			
Ice, m. p.............	0°	Gold, m. p.................	1062.4°
Water, b. p........	100.0+0.037 (p−760)	Copper, m. p. (in CO)	1082.6
Napthalene, b. p....	217.7+0.057 (p−760)	Li₂SiO₃...................	1201.
Benzophenon, b. p...	305.4+0.063 (p−760)	Diopside, m. p.............	1391.2
Cadmium, m. p......	320.2	Nickel, m. p. (in N₂).....	1452.3
Zinc, m. p..........	418.2	Cobalt, m. p. (in N₂).....	1489.8
Antimony, m. p(inCO)	629.2	Palladium, m. p..........	1549.2
Silver, m. p. (in CO).	960.0	Platinum, m. p...........	1755.

Fig. 15. Deviation of typical thermo-elements from standard curve.

For interpolation in every-day practice over this long range of temperatures we may use either an empirical equation or series of equations, or we may plot the temperatures and microvolts and draw a smooth curve through the points. The results of one method have no better claim to accuracy than the results of the other, for an empirical equation is essentially nothing but an imaginary curved ruler. A plotted curve on a scale large enough to get the requisite accuracy of reading would, however, take a sheet at least 30 feet square. But if instead of plotting microvolts directly against degrees, we plot the *deviation* from the straight line, $e = 10t$, the sheet required is reduced to about 3 feet square. If further, we plot the deviations of each element from an *arbitrary standard curve*, instead of the deviations from a straight line, the usual 50 cm. × 40 cm. sheet is ample.

The figures of Table XVII represent such a curve, which lies very close to the actual curve for the standard thermo-element E used in the work on the nitrogen thermometer. The deviations of various other elements, in use in the laboratory, from this standard are plotted in Fig. 15. These curves are obtained by plotting the differences between the reading of the element and that of the assumed standard at each calibration point.

An example will serve to make clear the method of converting microvolts into degrees with this table and curve. It is desired to find the temperature corresponding to a reading of 8931 microvolts on element Z. It is evident from the table that the temperature is in the neighborhood of 950°. At about this temperature, element Z reads 92 microvolts below the assumed standard; adding 92 microvolts to 8931 gives 9023 microvolts as the corresponding standard reading, and this by interpolation in the table gives 952.3°. The tenths, of course, mean little in absolute value; but temperature *differences*, in case measurements are made with similar elements under similar conditions, can be obtained if need be to tenths of a degree.

TABLE XVII.—STANDARD CURVE OF ELEMENT PT: (90 PT 10 RH) FROM 0° TO 1755°.

t	e	Diff.	t	e	Diff.	t	e	Diff.
0		55	300	2315	92	580	5026	101
10	55	57	305.4 Benzo.	2365		590	5127	102
20	112	60	310	2407	93	600	5229	102
30	172	62	320	2500	93	610	5331	103
40	234	63	320.2 Cd	2502		620	5434	103
50	297	65	330	2593	93	629.2 Sb	5529	
60	362	67	340	2687	94	630	5537	103
70	429	69	350	2781	94	640	5640	104
80	498	71	360	2875	94	650	5744	104
90	569	72	370	2969	95	660	5848	104
100	641	73	380	3064	95	670	5952	104
110	714	75	390	3159	95	680	6056	105
120	789	77	400	3254	96	690	6161	105
130	866	78	410	3350	96	700	6266	105
140	944	79	418.2 Zn	3429		710	6371	106
150	1023	80	420	3446	96	720	6477	106
160	1103	81	430	3542	97	730	6583	106
170	1184	82	440	3639	97	740	6689	106
180	1266	83	450	3736	97	750	6795	107
190	1349	84	460	3833	98	760	6902	107
200	1433	85	470	3931	98	770	7009	108
210	1518		480	4029	98	780	7117	108
217.7 Napht.	1584	86	490	4127	99	790	7225	108
220	1604	86	500	4226	99	800	7333	108
230	1690	87	510	4325	99	810	7441	109
240	1777	88	520	4424	100	820	7550	109
250	1865	89	530	4524	100	830	7659	110
260	1954	89	540	4624	100	840	7769	110
270	2043	90	550	4724	100	850	7879	110
280	2133	91	560	4824	101	860	7989	111
290	2224	91	570	4925	101	870	8100	111

Table XVII.—Standard Curve of Element Pt: (90 Pt 10 Rh) from 0° to 1755°—Concluded.

t	e	Diff.	t	e	Diff.	t	e	Diff.
880	8211	111	1170	11572	120	1470	15183	121
890	8322	112	1180	11692	120	1480	15304	121
900	8434	112	1190	11812	120	*1489.8 Co*	*15423*	
910	8546	112	1200	11932	120	1490	15425	121
920	8658	113	1210	12052	120	1500	15546	120
930	8771	113	1220	12172	120	1510	15666	121
940	8884	113	1230	12292	120	1520	15787	121
950	8997	114	1240	12412	120	1530	15908	121
960	9111	114	1250	12532	120	1540	16029	121
960.0 Ag	*9111*		1260	12652	120	*1549.2 Pd*	*16140*	
970	9225	114	1270	12772	120	1550	16150	120
980	9339	115	1280	12892	120	1560	16270	121
990	9454	115	1290	13012	120	1570	16391	121
1000	9569	116	1300	13132	120	1580	16512	120
1010	9685	116	1310	13252	120	1590	16632	121
1020	9801	116	1320	13372	120	1600	16753	120
1030	9917	117	1330	13492	120	1610	16873	120
1040	10034	117	1340	13612	121	1620	16993	120
1050	10151	117	1350	13733	121	1630	17113	120
1060	10268	118	1360	13854	121	1640	17233	120
1062.4 Au	*10296*		1370	13975	120	1650	17353	120
1070	10386	118	1380	14095	121	1660	17473	120
1080	10504	118	1390	14216	121	1670	17593	120
1082.6 Cu	*10535*		*1391.2 Diops.*	*14231*		1680	17713	120
1090	10622	118	1400	14337	121	1690	17833	120
1100	10740	118	1410	14458	121	1700	17953	120
1110	10858	119	1420	14579	120	1710	18073	120
1120	10977	119	1430	14699	121	1720	18193	120
1130	11096	119	1440	14820	121	1730	18313	120
1140	11215	119	1450	14941	121	1740	18433	120
1150	11334	119	*1452.3 Ni*	*14969*		1750	18553	120
1160	11453	119	1460	15062	121	*1755. Pt*	*18613*	

The use of Table XVII and the deviation-curve (Fig. 15) avoids the calculation and recalculation of thermo-element curves and the tabulation of their readings. If the calibration of an element changes by a few microvolts, the deviation-curve is merely raised or lowered by a corresponding amount. If the value adopted for one of the calibration points is changed, the corresponding reading in microvolts of the assumed standard is also changed, and all the deviation-curves take a slightly different course in the neighborhood of that point. The table and curves make it possible, furthermore, to estimate temperatures (with an accuracy of perhaps 5°) with a new thermo-element, by simply calibrating it at, say, two points such as silver and diopside, and thus locating it among the family of deviation-curves.

20. RELATION OF THERMAL E. M. F. TO COMPOSITION.

In the course of the work on the nitrogen thermometer, the standard 10 per cent elements were compared with elements whose alloy wires contained 1 per cent and 15 per cent rhodium. The E. M. F. of the 20 per cent alloy, of which the bulb was made, was determined by two methods,[1] in order to evaluate the different readings on the nitrogen-thermometer bulb. To make the series more complete, a 5 per cent alloy was obtained from Heraeus and its readings against pure platinum were compared with the standards.

A similar series of comparisons was made in 1892 by Holborn and Wien,[2] using alloys with 9, 10, 11, 15, 20, 30, 40, and 100 per cent rhodium. This work was done, however, just at the beginning of the careful work of Mylius on the separation of the platinum metals, and the alloys then available were not pure. In the lower percentage alloys, different elements of the same nominal composition gave E. M. F.'s differing by 10 per cent or more, and varying differently with temperature. In the higher percentages, the E. M. F. varies little with the composition, and the results have therefore some value in indicating the course of the curve of E. M. F. and composition. The data have been corrected to our temperature scale, and also for the difference in E. M. F. standards.

Holborn and Day[3] in 1899 obtained the E. M. F. of pure platinum against two samples of pure rhodium up to 1300°. The data have been corrected to correspond to our temperature scale.

Waidner and Burgess[4] measured the E. M. F. of the 10 per cent against the 20 per cent alloy, at various points up to 1755°, using two samples. The addition of this value to the E. M. F. of the 10 per cent alloy against pure platinum gives an independent check on our direct measurements with the 20 per cent alloy. As shown by Fig. 16, the agreement is very good.

The summarized data are given in Table XVIII. For the 10 per cent alloy three values are given: first, the lowest-reading of the twelve elements used with the nitrogen thermometer; second, the highest-reading; and third, the standard element E.

The frequent comparisons of the platinum and platinrhodium wires of the standard 10 per cent elements during the work on the nitrogen thermometer, show that the differences among them are due partly to the platinum wire

[1]Page 67.
[2]L. Holborn and W. Wien, Uber die Messung hoher Temperaturen, Ann. Phys., 47, 107-134, 1892.
[3]Thermo-electricity in certain metals, Amer. Jour. Sci. (4), 8, 303-308, 1899; Ann. d. Phys. 2, p. 522, 1900. Sitzb. Berl. Akad., 1899, 691-695.
[4]Bull. Bur. Stds,. 3, p. 200, 1907.

and partly to the alloy. Element Z, for instance, reads lower than E chiefly because the platinum wire of Z is more impure than that of E; the effect of this impurity is partly neutralized by an apparently larger amount of rhodium in the alloy wire. This appears from the data in the table below, which show comparisons between several typical 10 per cent elements. The purest platinum appears to be that of J. If the thermo-electric effect of rhodium is proportional to its percentage from o to 1 per cent, then about 0.05 per cent rhodium in platinum wire would be sufficient to produce the difference between Z and E. The data are in microvolts.

TABLE XVIII.—THERMAL E. M. F. OF PURE PLATINUM AGAINST PLATINUM-RHODIUM ALLOYS, IN MILLIVOLTS.

t	1 p. ct.	5 p. ct.	10 p. ct.			15 p. ct.	20 p. ct.	30 p. ct.[1]	40 p. ct.[1]	100 p. ct.[2]
			Low.	High.	Stand-ard.					
100°	0.21	0.55	0.63	0.64	0.64	0.65	....			0.65
200	0.42	1.18	1.41	1.43	1.43	1.50	....			1.51
300	0.63	1.85	2.28	2.32	2.32	2.41	....	2.34	2.45	2.57
400	0.84	2.53	3.21	3.26	3.25	3.45	3.50	3.50	3.64	3.76
500	1.05	3.22	4.17	4.23	4.23	4.55	4.60	4.74	4.93	5.08
600	1.25	3.92	5.16	5.24	5.23	5.71	5.83	6.06	6.31	6.55
700	1.45	4.62	6.19	6.28	6.27	6.94	7.18	7.49	7.80	8.14
800	1.65	5.33	7.25	7.35	7.33	8.23	8.60	9.01	9.37	9.87
900	1.85	6.05	8.35	8.46	8.43	9.57	10.09	10.67	11.09	11.74
1000	2.05	6.79	9.47	9.60	9.57	10.96	11.65	12.42	12.94	13.74
1100	2.25	7.53	10.64	10.77	10.74	12.40	13.29	14.33	14.99	15.87
1200	2.45	8.29	11.82	11.97	11.93	13.87	14.96	16.39	17.13	18.10
1300	2.65	9.06	13.02	13.18	13.13	15.38	16.65	18.51	19.51	20.46
1400	2.86	9.82	14.22	14.39	14.34	16.98	18.39	20.67	21.73	....
1500	3.06	10.56	15.43	15.61	15.55	18.41	20.15	....		
1600	3.26	11.31	16.63	16.82	16.75	19.94	21.90	....		
1700	3.46	12.05	17.83	18.03	17.95	21.47	23.65	....		
1755	3.56	12.44	18.49	18.70	18.61	22.31	24.55	....		

[1]Holborn and Wien, 1892, loc. cit.   [2]Holborn and Day, mean value, 1899, loc. cit.

The data of Table XVIII are plotted in Fig. 16, which shows the relation between temperature and thermal E. M. F. for various alloys. The 30 per cent and 40 per cent curves represent the data of Holborn and Wien. The curve for pure rhodium represents the mean of the two samples by Holborn and Day. There is no indication of a break in any of the curves over the entire range of temperature.

In Fig. 17, the data of Table XVIII are plotted to show the relation of the thermal E. M. F. at various constant temperatures to the composition of the alloy wire, the cold junction being in every case at o°. At all tem-

Element.	E. M. F. of Pt wire against Pt of E at 1500°.	E. M. F. of Pt-Rh wire against Pt-Rh of E at 1500°.	Difference between elements.
Y	+ 12	+75	+ 63
Z	+177	+67	−110
A	+ 75	+47	− 28
F	+ 7	+ 1	− 6
J	− 9	+ 1	+ 10

peratures the E. M. F. increases very rapidly with the first additions of rhodium, and at 20 per cent the value has already reached 81 to 93 per cent of the E. M. F. of platinum against pure rhodium.
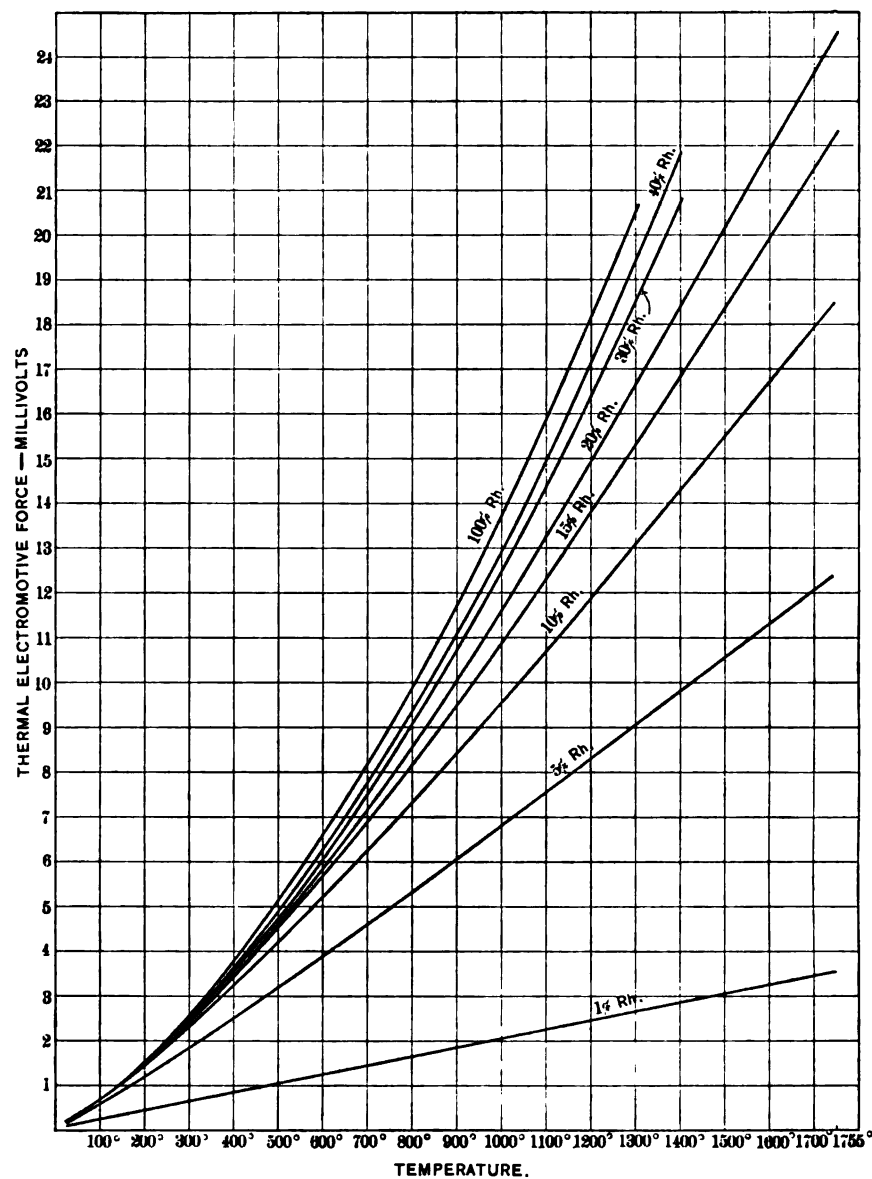

Fig. 16. Relation of temperature to thermal electro-motive force of platinum against platinum-rhodium alloys.

The thermo-electric power, or rate of change of E. M. F. with temperature $\frac{de}{dt}$ is plotted in Fig. 18, against the atomic concentration of the alloy. The values are in microvolts, against pure platinum. The curves for all tem-

peratures are similar in form and approach the curve for 1755° as an envelope.

In a recent study of the thermo-electric properties at low temperatures of the alloys of tellurium with antimony, tin, and bismuth, and of antimony with silver, Haken[1] comes to the conclusion that a thermo-electric curve of the form of those in Fig. 18 accompanies the formation of a solid solution between the end components, while compounds are marked by sharp maxima or minima. The thermo-electric curves of the systems copper-cobalt, by Reichardt;[2] copper-nickel, by Feussner and Lindeck;[3] and silver-zinc, by Puschin and Maximenko,[4] show a similar relationship between the form of the curve and the constitution of the alloy. More recently, E. Rudolfi[5] has published a study of these relationships for eight pairs of metals.
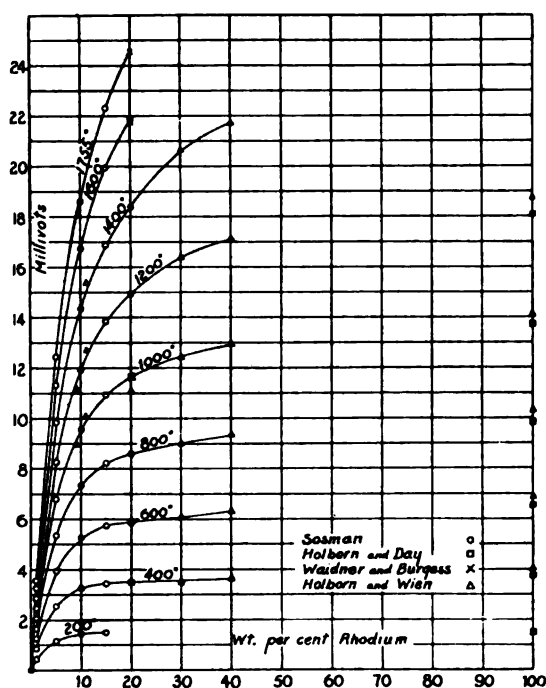

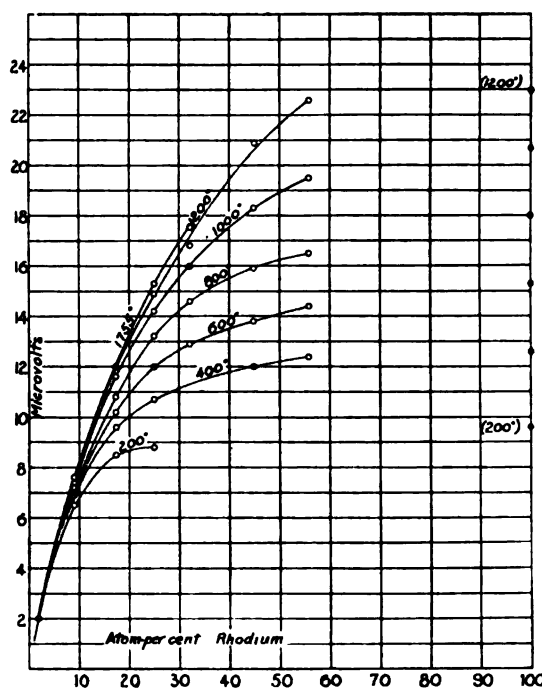FIG. 17. Relation of thermal electromotive force, e, to composition of platinum-rhodium alloys.

FIG. 18. Relation of $\frac{de}{dt}$, thermo-electric power against platinum, to atomic composition.

The alloys of platinum and rhodium have not been studied microscopically or thermally, but measurements in our carbon-tube furnace showed that the melting-points of the 1 per cent and 5 per cent alloys are higher than 1755°. The melting-point of the 10 per cent alloy is given by von Wartenberg[6] as 1830°, and of pure rhodium as 1940°. It is very probable, therefore, that platinum and rhodium form solid solutions at least as far as 55 atomic per cent rhodium, with no compounds, over the range of temperature covered by our data.

[1] Verh. deutsch. phys. Ges. 12, 229-239, 1910. Ann. d. phys., 32, 291-336, 1910.
[2] Ann. d. Phys., 6, 832-55, 1901.
[3] Wiss. Abh. Phys.-Tech. Reichsanstalt, 2, p. 515, 1895.
[4] Jour Russ. Phys. Chem. Ges., 41, 500-524, 1909.
[5] Zeitschr. anorg. Chem., 67, 65-96, 1910.
[6] Verh. Deutsch. Phys. Ges., 12, 121-127, 1910.

21. SUMMARY.

It is now something over five years since the Geophysical Laboratory took up the task of redetermining the absolute temperature scale from 400° to 1100° with the nitrogen thermometer, and of extending it, if it should prove practicable to do so, to 1600° C., covering the region in which are found most of the mineral relations which it is the chief purpose of the laboratory to study. Two preliminary publications have been made during the investigation. One, a brief summary of preliminary work up to 1100°, was given before the National Academy of Sciences and the American Physical Society in April, 1907;[1] the second covered the same ground at considerable length in 1908.[2] A final paper[3] extending the observations to 1550°, and a supplementary paper[4] on the use of thermo-elements throughout the entire range from zero to melting platinum appeared in 1910 and completed the work contemplated under the original plan.

The gas-thermometer problem at the present stage of its development has become primarily a problem for experimental study with two definite purposes, one to increase the accuracy of the measurements, the other to increase their range. The application of the gas laws is no longer subject to serious question. The progress of recent years has given us electric heating in place of gas and the consequent possibility of controlling the temperature with great certainty and exactness. It has also given us the metal bulb with a definite and measurable expansion coefficient and capable of holding the expanding gas without loss. It has discovered a gas which does not diffuse through the bulb or react with it chemically, which does not dissociate within the limits of practicable measurement, and of which the expansion can be expressed with reasonable certainty in terms of the Kelvin thermodynamic scale whenever it may prove necessary or desirable to do so. It has also discovered the source of the errors in the thermo-elements and a way to avoid them.

In 1904 Professor Holborn of the Reichsanstalt increased the range of this scale as far as 1600° C., the probable error of the new portion being 10°. Simultaneously with this effort, work was begun at the Geophysical Laboratory in Washington with a view to increasing the accuracy of the scale, first over the existing range (to 1150°), and later, as much beyond this point as it should prove practicable to go.

No attempt will be made to offer an inclusive summary of the whole investigation. It is a record of experimental measurements covering an unusually wide range of details which do not admit of brief classification. The errors which have heretofore been present in measurements with the nitrogen thermometer have been reduced by the present investigation to about one-fourth their former magnitude and the certainty of their evaluation is at least proportionately increased.

The particular points to which we have given most attention are the following:

(1) To provide a uniform temperature about the bulb by a suitable arrangement of electric-heating coils and diaframs.

[1] Abstract, Phys. Rev., 24, 531, 1907.   [3] Amer. Jour. Sci. (4), 29, 93–161, 1910.
[2] Amer. Jour. Sci. (4), 26, 405–463, 1908.   [4] Amer. Jour. Sci. (4), 30, 1–15, 1910.

(2) To inclose the furnace in a gas-tight bomb in which the pressure outside the bulb can be maintained equal to that within for all temperatures. This offers three distinct advantages: (a) it provides against the deformation of the bulb through differences of pressure within and without in the region of highest temperatures, where the bulb material becomes softer; (b) by using the same gas within and without, there is no tendency for it to diffuse through the bulb wall; (c) it enables the initial pressure to be varied within considerable limits, thereby increasing both the scope and sensitiveness of the manometer. The sensitiveness in our instrument with this arrangement was about three times that of the Reichsanstalt.

(3) The expansion of the bulb material was determined with great care and is probably accurate within 0.5 per cent.

(4) The unheated space between the bulb and manometer has been reduced until the total correction in this hitherto uncertain region amounts to less than $4°$ at $1100°$. An error of 5 per cent in the determination of its volume or temperature distribution is, therefore, practically negligible.

It is probable that these changes serve to reduce the uncertainty hitherto prevailing in the correction factors which require to be applied to the gas thermometer in the region of $1100°$ to less than one-tenth of its former magnitude. Furthermore, these improvements are equally applicable throughout the region above $1100°$ as far as the present measurements have extended (to $1550°$).

The chief source of present uncertainty is the temperature distribution over the surface of the bulb in an air bath. It would be possible to eliminate this error in the lower portion of the scale by substituting a liquid bath which could be stirred. In fact, this was done for temperatures below $500°$ in the earlier work of Holborn and Day, but has not so far been tried in the present investigation because of the relatively secondary importance of the lower temperatures to the ultimate purpose of the investigation (the study of silicates). For the higher temperatures no satisfactory liquid bath has been found.

The treatment of experimental errors in a complicated problem of this kind is obviously a matter into which the personal equation enters largely. The only sure method is to make their total magnitude disappearingly small, and to this end our efforts have been directed wherever possible. Errors due to failure of the pressure to return to its initial zero after heating to a high temperature, which are due to permanent changes in the volume of the bulb, or to absorption or loss of gas, are entirely negligible in the present instrument. This source of error is of a particularly intangible kind and has clung to all the earlier work in gas thermometry like a haunting evil spirit.

Another classical source of uncertainty to which attention has already been called, lies in the unheated connecting link between the hot bulb and cold manometer in which the volume and temperature conditions have been exceedingly difficult to establish. It is also reduced to practically insignificant magnitude in the present instrument and can be still further diminished if necessary.

Still a third difficulty which was discovered in this laboratory[1] soon after

[1]W. P. White. "The Constancy of Thermo-elements." Phys. Rev., 23, 449–474. 1906.

this investigation began and which at once assumed serious proportions, arises from the gradual contamination of the auxiliary thermo-elements by iridium vapor from the heating coil, the bulb, or any platinum crucibles or diaframs containing this metal which are exposed by accident or design in the furnace at extreme temperatures. This absorption of iridium vapor (in a minor degree of rhodium vapor also) which has been an important though unrecognized factor in all previous work in which thermo-elements were used (beginning with Barus), has the effect of making the thermo-elements read lower as contamination increases. These effects also have been reduced to negligible magnitude in all the observations of the present series subsequent to the preliminary set (Table II), which has not been used in calculating the results.

The remaining correction factors are numerous, but with the exception of the expansion of the bulb, which has been very carefully determined, are not only small but are unlikely to become cumulative in a particular case. The temperature correction for the mercury columns of the manometer, for example, which is of a magnitude to catch the eye in the table on p. 69, and to which our attention has been explicitly called, is in fact an error of very harmless character in practice in the magnitude in which it here enters. It appears as an error of the same order of magnitude and same sign in two quantities, the difference of which is used in the computation of temperature. It varies but little in the observations of a single day and does not increase with the temperature. There is therefore little of real uncertainty to be apprehended from this source. The same is true of many of the other minor corrections to which the final values are subject.

In general it may be said, for the information of those who have not a first-hand acquaintance with the gas thermometer, that the danger lies in relations which become more uncertain as the temperature advances, such for example as the distribution of temperature about the bulb, which is continually changing in an air bath at extreme temperatures, and in the expansion of the bulb material in the same region. Changes in the temperature of the bulb wall can be observed by grouping a number of thermo-elements about it (eight were used for this purpose in our experiments) and corrections can be applied for the differences observed. In the experiments here recorded the temperature control was very perfect, even at the highest temperatures, and differences of temperature on the surface of the bulb amounting to a whole degree were rarely observed.

It is, however, a little difficult to make positive assertions about the temperature of the gas in a containing vessel when the temperature on its surface shows differences of 10 degrees or more, as has usually been the case in the earlier high-temperature gas-thermometer measurements. The same may be said of the expansion of the bulb itself; a determination of the expansion coefficient, however accurate for the range of temperatures from zero to 100°, or to 500°, affords insufficient basis for an extrapolation to 1600°, particularly since the expansion has been definitely shown not to be a linear function, but to increase with some rapidity with the temperature in the case of the platinum alloys which serve the purpose best. Such haphazard extrapolation appears particularly rash when it is recalled that this is

the most important and largest correction factor to which gas-thermometer observations are now subject and one which can not be avoided or materially diminished in magnitude. Inasmuch as the bulb itself is practically inaccessible for the purpose of measuring its expansion, this difficulty was met in the present experiments by having a half-meter bar made up at the same time as the bulb and from the same material. The linear expansion of this bar was measured directly in a special form of comparator (p. 27) up to 1400°; beyond this temperature the bar sagged under its own weight and accurate measurements were no longer practicable. From 1400° to 1550°, therefore, we were also obliged to resort to extrapolation; but with consistent measurements (maximum difference 0.5 per cent), several times repeated at every 50° interval from 300° to 1400°, the extrapolation over an additional 150° appears reasonably free from uncertainty unless indeed the alloy should be found to possess an inversion point in that region. But such a point would certainly show itself in the form of a break in the series of gas-thermometer observations themselves and probably also in the electromotive force of thermo-elements of this composition, and of such irregularities the observations reveal no trace.

By way of conclusion of this effort to reduce uncertainty to a minimum, a final attempt was made by the present observers to ascertain the order of magnitude of the aggregate uncertainty in the results at 1100° by experimental means. A new furnace was prepared with a very thick (1 inch) wall (the original furnaces had no wall inside the heating coil) and wholly different arrangements for distributing the heat within it (see Fig. 10 and description, p. 56). In this furnace all the correction factors which result from heat distribution and the contamination of thermo-elements from the heating coil were radically altered, but the temperature measurements at the copper melting-point agreed with the mean of all the determinations at this temperature identically (1082.6°).

The interpretation of these measurements in terms of the melting-points of readily available substances encounters certain difficulties. The melting-point of pure salts is not sufficiently sharp and is somewhat difficult of interpretation. The metals which have commonly been used for the purpose, with the possible exception of nickel and cobalt, are, however, obtainable in sufficiently uniform purity to guarantee an accuracy within 1° at the higher temperatures.

No effort has been made to prepare metals in our own laboratory of exceptional purity, for the reason that such metals would not be available for general use and would therefore be of little service. We have accordingly adopted metals which are carried permanently in stock by dealers whose names are given in connection with each, from whom the same metal in a nominal quality equal to that which we used can be readily obtained. We have analyzed these with extreme care to show the exact content of the sample supplied us. We have duplicated the purchases ourselves, and have found no errors greater than 1° in their melting-point determinations.

Another difficulty arises from the fact that the melting-points of the purest metals available for use as constants in reproducing a high-temperature scale (zinc, silver, gold, copper, and palladium) are distributed in such a way that, although they may be *located* upon the gas-thermometer

scale with a probable error not greater than 0.5°at low temperatures or 1° at high temperatures, the calculation of a similar curve passing through these points may not suffice to *reproduce* the scale with this accuracy. In the region midway between zinc (418.2°) and silver (960.0°) the error of interpolation may amount to 2°, and between copper and palladium to 5°, even with metals of exceptional purity. Extrapolation is even more uncertain. This can be avoided by locating a sufficient number of intermediate points which are equally trustworthy, if such can be found. We have not been fortunate enough to find points which fulfil these conditions quite as well as the metals named above, but if the table (Table XVII) offered in the text is accurately followed, there is little danger of serious errors, even in inexperienced hands.

In order to facilitate as far as possible the application of these results in general practice, a typical thermo-element curve has been tabulated in small 10° intervals throughout its entire length from melting ice to melting platinum, together with a diagram showing the character and magnitude of the variation from this curve, which may be expected to appear in other thermo-elements of the same nominal composition (90 parts platinum, 10 parts rhodium). With a new platin-rhodium thermo-element of undoubted homogeneity, but unknown constants, it is quite practicable with this table to prepare a curve of its electromotive force for any temperature with sufficient accuracy for most purposes (say 5° at low temperatures and ± 10° above 1200°) from a single determination in melting copper. If this accuracy is inadequate, additional determinations of its electromotive force at other temperatures of the list below will help to fix it more closely.

There is no sure way to guard against the contaminating influence of metal vapors upon a thermo-element in laboratory or industrial practice, although glazed porcelain is usually effective. There are very simple and rapid means of detecting contamination in an element and determining its distribution, and with a second element at hand for an occasional comparison there is little of serious danger from this cause. In any case, the slight inconvenience is well worth while wherever considerable accuracy is sought, for there is no other device yet available, in the region between 1100° and 1600°, which is comparable with the thermo-element in sensitiveness and general practicability.

In conclusion, the list of standard melting-points is given in tabular form, together with an estimate of the degree of trustworthiness to be accorded to each. Beside it for convenient comparison is the present Reichsanstalt scale. It may be added that no indication of a limit to the temperature attainable with the nitrogen thermometer or to its ultimate accuracy was discovered during the present investigation.

TABLE XIX.

Substance.	Point	Atmosphere.	Crucible.	Temperature.	Reichs-anstalt scale.
Zinc......	Melting and freezing	Air...............	Graphite......	$418.2°\pm0.3$	$419.0°$
Antimony.....Do......		Carbon monoxide.....Do........		629.2 ± 0.5	630.6
Silver........Do......		Do...............	Do........	960.0 ± 0.7	961.5
Gold........Do........		...Do.............	Do........	1062.4 ± 0.8	1064.0
Copper.......Do.......		...Do.............	Do........	1082.6 ± 0.8	1084.1
Diopside . (pure)	Melting.....	Air.............	Platinum......	1391.2 ± 1.5	
Nickel...	Melting and freezing.	Hydrogen and ni-trogen.	Magnesia and magnesium aluminate.	1452.3 ± 2.0	
Cobalt.......Do........		...Do..........	Magnesia......	1489.8 ± 2.0	$1575.$[1]
Palladium....Do......		Air.............	Pure magnesia.	1549.2 ± 2.0	
Anorthite. (pure)	Melting........	...Do...........	Platinum......	1549.5 ± 2.0	

In addition, the following temperatures were incidentally obtained:

Cadmium.	Melting and freezing.	Air.............	Graphite......	$320.0°\pm0.3$	321.7
Aluminum	Freezing....	Carbon monoxide ....Do........		658.0 ± 0.6	$657.$
Li_2SiO_3...	Melting	Air.............	Platinum......	$1201. \pm1.$	
Platinum .	Melting.....	Air...........................		1752[2] 1755[3] $\pm5.$	

[1] Holborn and Valentiner, loc. cit.   [2] Extrapolation, thermo-electric.   [3] Extrapolation, optical.

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        Washington, D. C., March, 1911.